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Assessment of PUFF
A Dispersion Model for Smoke Management

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ASSESSMENT OF PUFF

A DISPERSION MODEL
FOR SMOKE MANAGEMENT

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INTRODUCTION

The objective of this study was to assess the performance of PUFF, a three-dimensional dispersion model for smoke emissions from broadcast burning of western species logging debris. Our evaluation centered on the spatial performance of the model with respect to three parameters: direction, or azimuth, of the plume trajectory; height of the smoke plume; and range, or distance downwind, of the dispersing smoke plume. Our approach was to acquire airborne observations of several dozen smoke plumes, digitally recording the elevation, trajectory, and temporal aspects of each plume over the duration of active combustion. These data were acquired to enable a quantitative comparison of the observation data with respective data derived from model runs of PUFF. We attempted to stress the model by obtaining data across the continuums of airmass stability, fire intensity, and geographic location. Furthermore, our strategy was to include qualitative assessments of the model with respect to end-user constraints and needs, operational efficiency, and the architecture of the user interface.

This assessment was designed to determine under which sets of fire, weather, and terrain parameters PUFF could be expected to provide useful information to the manager of a prescribed fire program. Our observations were designed to provide insight as to when it would fail, as well.

In this report we will first present a summary of model expectations, components of the model, and a history of the development of PUFF and EPM. Next, our observations of 23 fires and their respective weather and plume dynamics will be presented, followed by quantitative as well as qualitative results of our assessment. Finally, we present general discussion comments on the modeling of surface wind flow and about PUFF's performance based on meteorological considerations.

BACKGROUND

In consideration of the model as well as of this assessment, it may be helpful first to consider several specifications included in the Request for Proposal for the development of this dispersion model.

Scope of the Contract

The RFP for the model specifies that the model be a *"...decision-making tool for smoke managers to avoid intrusion into population centers, over highways, and into or over Class I wilderness areas."*

The scope of the contract can be summarized by the following:

1. The model must run on a "generic", 386-based personal computer.
2. The model must utilize digital terrain data to process and display plume rise, trajectory, and dispersion in three dimensions (latitudinal, longitudinal, and elevation).
3. The model must be capable of processing multiple plumes, at different locations, ignition times, and elevations.
4. The model must include site-specific data on fuels, weather, burning prescription, and fire/ignition parameters.

In addition, the RFP has specified the operator level to be *"...a burn boss or fire management specialist with some familiarity with basic meteorology; however, most operators will not have an in-depth understanding of meteorology or mathematical modeling."*

Components of the Model

PUFF is comprised of five logical components:

1. **Emission Production Model (EPM).--** A source-strength model for predicting energy flux and emissions production over time from prescribed broadcast burns in western logging debris. EPM, developed by the PNW Research Station, is an empirically-derived set of functions fitted to ignition, flaming, and early smoldering portions of a prescribed fire. EPM uses empirical field observations or estimates, and its design philosophy enables managers to "game" their projects by manipulating ignition patterns, fuel amounts and condition, and weather. EPM is the "front-end" of PUFF and other dispersion models. PUFF uses EPM output in 3-minute increments.

2. **Digital Terrain Data.--** The terrain data used by PUFF includes Washington, Oregon, Montana, Idaho, and parts of California and British Columbia. The digital terrain model (DEM) has a spatial resolution of 30 seconds (about 1 kilometer).

3. **Meteorology.--** Weather data used by PUFF is provided through a third-party vendor in the form of NESTED GRID MODEL (NGM). The NGM data are projected at 6 hour increments from analysis time (at either 0Z or 12Z) to 48 hours. The gridded data has a spatial resolution of about 90 kilometers. PUFF interpolates sub-grid data from the NGM to 1 kilometer in space and 3 minutes in time.

4. **Plume Rise.--** Smoke is bouyed into the atmosphere by PUFF through a semi-empirical plume rise model, as

described in the User's Manual appendices. The plume rise model uses energy release rates generated by EPM.

5. **Smoke Trajectory and Dispersion.--** The smoke dispersion algorithm assumes a Gaussian distribution puff that is advected horizontally by interpolated winds. In addition, sub-grid eddies are simulated by random grid components. These functions are further described later in this report as well as in the appendices of the User's Manual.

History of the Project

Ideally, the development of PUFF, improvements and enhancements to EPM, and a robust assessment of the model performance should have proceeded serially. However, in the interest of providing a product useful to (and accurate enough for) the end-user, these processes have proceeded more or less concurrently. Following is a summary chronology of the project.

March, 1990	Bid solicitation.
Spring 1990	Contract awarded to WYNDsoft, Inc.
January, 1991	WYNDsoft presents preliminary model.
Summer, 1991	Airborne plume observations.
Summer, 1991	EPM scientific review and enhancements.
March, 1992	First draft, assessment version of PUFF.
June, 1992	Airborne plume observations concluded.
February, 1993	WYNDsoft contract completed.
April, 1993	PNW assessment to implementation team.
May, 1993	PNW receives Beta Version to implement.

FIELD OBSERVATION METHODS

Our field observations of smoke plumes from prescribed fires were made from a fixed-wing aircraft. We developed a customized, tandem-datalogging GPS system to record spatial and temporal data simultaneously with attribute data regarding the aircraft position relative to the plume's source, centerline, edges, and downwind terminus. The attribute data were subsequently used to parse out the GPS data specific to an individual observation pass flown along a plume's trajectory. The data from each of these passes were then compared with cross-section data modeled by PUFF for the respective time period of the burn. Both the observation and PUFF-modeled vectors were represented in four dimensions: latitude, longitude, elevation, and time.

Twenty three individual smoke plumes were observed on six separate days. The three Region Six National Forests participating in this assessment were Siuslaw, Willamette, and Wenatchee. Of the 23 plumes observed, 5 were on the Siuslaw, 11 were on the Willamette, and 7 were on the Wenatchee. Table 1 presents information relevant to the 23 fires.

Upon notification of a planned prescribed burn, we deployed our equipment in a twin-engine, Piper Seneca II aircraft. When a plume was being observed, both the pilot and the observer attempted to locate and fly an observation pass along the centerline of the plume. Passes were made from the source downwind towards the plume terminus, or tail, and from the tail to the source of the plume. Passes were made as close to initiation of the burn as possible, and follow-up passes were made near the end of the burn day, when active convection and dispersion were diminished. Concentration data were not acquired. Determination of the plume edges and tail were ocularly made by the pilot and observer. All location and time-stamp data were digitally recorded with concurrent recording of the observer's position relative to the plume (e.g. at the source; centerline downwind; centerline towards the source; out the tail).

Table 1. Fire-specific data.

Burn #	>	Burn Code	Burn Name	Forest Name	District Name	Location Coordinates		Acres	Burn Date	Ignite Time	Wx Summary				.NGM File	Gridded Wx	
						Latitude	Longitude				M	S	W	D		Date	Hour
						– – (DecDeg) – –				(PDT)	(see footnote)				(f_name)		(Z)
1		PV3	Pole Valley #3	WEN	L.Wenatchee	47.862	120.712	24	5/2/91	0930	D	U	W	E	05029112	N/A	N/A
2		PR1	Pine Ridge #1	WEN	L.Wenatchee	47.876	120.682	28	5/2/91	1130	D	U	W	E	05029112	N/A	N/A
3		SW25	Swamper 25	WEN	Naches	46.927	121.093	21	5/13/91	1130	W	S	M	W	05139112	N/A	N/A
4	>	UPC8	Upper Cayouse 8	WIL	Oakridge	43.820	122.197	16	6/7/91	0930	M	S	M	W	06-07-91	6/7	12
5	>	ASTRO3	Astro 3	WIL	Rigdon	43.398	122.374	51	6/7/91	0945	M	S	M	W	06-07-91	6/7	12
6	>	FLY1	Flying Cayouse 1	WIL	Oakridge	43.831	122.156	10	6/7/91	1000	M	S	M	W	06-07-91	6/7	12
7	>	JJ3	Joe Jaguar 3	WIL	Sweet Home	44.352	122.141	24	6/8/91	0830	M	S	M	W	06089114	6/8	12
8	>	COY5	Coyote Mtn. 5	WIL	Oakridge	43.638	122.232	23	6/8/91	0945	M	S	M	W	06089114	6/8	12
9	>	TRP3	Trail Pyramid 3	WIL	Sweet Home	44.502	122.102	22	6/8/91	1045	M	S	M	W	06089114	6/8	12
10	>	LS1	Longshot 1	WIL	Oakridge	43.854	122.166	30	6/8/91	1045	M	S	M	W	06089114	6/8	12
11	>	NH2	North Horse 2	WIL	McKenzie	44.160	122.065	31	6/8/91	1215	M	S	M	W	06089114	6/8	12
12	>	PG9	PG Way 9	WEN	Naches	46.594	121.296	29	6/18/91	1200	M	U	M	W	06189109	6/18	12
13	>	PG14	PG Way 14	WEN	Naches	46.591	121.297	13	6/18/91	1500	M	U	M	W	06189109	6/18	12
14	>	PN12	Panther 12	WEN	Naches	47.075	121.195	14	6/19/91	0930	M	U	M	W	06199114	6/19	12
15	>	SKY11	Sky Fall 11	WEN	Naches	47.109	121.380	23	6/19/91	1145	M	U	M	W	06199114	6/19	12
16	>	SKO21	Skookum 21	WIL	Oakridge	43.897	122.077	26	6/26/91	1100	M	S	M	W	06269111	6/26	12
17	>	SUN2	Sun Too 3	WIL	McKenzie	44.347	121.973	8	6/26/91	1500	M	S	M	W	06269111	6/26	12
18		PFB	Pitchfork Brushay	SIU	Alsea	44.377	123.850	24	7/19/91	0700	D	S	M	W	07199112	N/A	N/A
19		BLM	Sharp Ranch 2	SIU	BLM	44.447	123.632	24	7/19/91	0715	D	S	M	W	07199112	N/A	N/A
20		KLG	Keller Grass	SIU	Waldport	44.261	123.963	31	7/23/91	0430	M	U	M	E	07239106	N/A	N/A
21		GRANT	Grant Davis	SIU	Alsea	44.526	123.755	5	7/23/91	0530	M	U	M	E	07239106	N/A	N/A
22	>	NIAG	Niagara Bend #5	SIU	Hebo	45.233	123.630	43	7/27/91	0615	D	S	W	W	07279115	7/27	12
23		TRPYR4	Trail Pyramid 4	WIL	Sweet Home	44.512	122.117	28	5/5/92	1711					05059212	N/A	N/A

A ">" in the second column marks burns used in analysis; all others had bad or missing NGM Wx data.

Weather (WX) Code: (M)oisture– W=wet, M=moist, D=dry
(S)tability– S=stable, U=unstable
(W)ind strength– C=calm, W=weak, M=moderate, S=strong
(D)irection of wind

The NGM data relative to each burn was downloaded from a contract weather service (WSI). The NGM data sets were not always complete. Therefore, we chose to analyze data from days with the cleanest observation data. This reduced the number of observations available for a quantitative analysis from 23 to 15 burns. Observations used in this analysis are marked by a ">" character in column #2 of table 1.

WEATHER SUMMARY FOR TEST FIRES

Detailed fire observations including flight data were made on 23 prescribed burns that were ignited on 12 different days. Meteorological data from the National Weather Service (NWS) Nested Grid Model (NGM) are available from the 1200 Greenwich Mean Time (4 am Pacific Standard Time (PST)) model runs for each burn day. Data for 6 of the burn days was successfully downloaded from Weather Services Inc. (WSI) and is formatted such that all the PUFF programs correctly read and interpret the data. Therefore, these 6 WSI NGM files were used for this analysis.

The discussion that follows provides a general weather description for 4 am PST for the morning of the burns. The information was retrieved from national Weather Service observation data. For reference, the 850 mb level is about 5,000 feet msl elevation; the 700 mb level is at about 9,000 feet msl elevation. Surface wind information, pressure gradients and individual station comments are taken from the NWS surface weather observations from 0400 PST, 1200 PST and 1800 PST on the burn day. Stability was determined from the Showalter Stability Index.

DATE: 6/7/91. Three fires ignited (Burn codes ASTRO, UPC8,FLY1) on the Willamette National Forest.

700 mb level dominated by moderate northwesterly winds. 850 mb level experienced westerlies from the Willamette

Valley northward, and northerlies from about Medford southward.

Salem's sounding was moist below about 4300 feet and dry above. Medford was dry at all levels. Both soundings were stable.

The Salem to Pendleton pressure gradient drove west winds across the Cascades all day with the strongest pressure gradient at about 11 am; however the strongest surface winds from available observations occurred during the afternoon.

DATE: 6/8/91. Five fires ignited (Burn Codes COY5, LS1, JJ3, TRP3, NH2) all on the Willamette National Forest.

The upper level flow was very similar to the previous day.

Salem's sounding was saturated to about 11,000 feet and dry above. Medford's sounding was relatively dry with a moist layer at about 9000 feet. Both soundings were stable.

The east to west pressure gradient across the Cascades was weaker than on the previous day; however, west winds occurred and were strongest in the afternoon.

DATE: 6/18/91. Two fires ignited (Burn Codes PG9, PG14) on the Wenatchee National Forest. No sounding data in PUFF.

700 mb level: light south winds in Washington.
850 mb level: NE winds along the WA coast. Light to moderate E to NE winds east of the Cascades.

The airmass was moist and unstable.

Although surface southwest to northwest light winds occurred at Wenatchee and Yakima through the day, the pressure gradient across the Cascades was sufficiently weak so that Stampede Pass recorded light northeast veering to light southeast winds through the day.

DATE: 6/19/91. Two fires ignited (Burn Codes PN12, SKY11) on the Wenatchee National Forest. No sounding data in PUFF.

700 mb level: moderate E winds all of Washington
850 mb level:NE winds from Puget Sound to Eastern Washington, becoming stronger toward the east.

- - - PUFF ASSESSMENT - - -

The airmass was moist and unstable. Note, this date and 6/18/91 are the only two days with unstable atmospheric conditions and will therefore be used to test PUFF's performance for such. Note, these are also the only days with fires east of the Cascade crest.

Wenatchee maintained light west winds throughout the day. The pressure gradient across the Cascades was stronger than on the previous day which resulted in calm winds at Stampede Pass at 0500 PST, becoming light to moderate SW winds by 1700 PST.

DATE: 6/26/91. Two fires ignited (Burn codes SKO21,SUN2) on the Willamette National Forest.

700 mb level: West winds central Oregon and south. Light winds further north.
850 mb level: Clockwise circulation around light wind area in Central Oregon. S or SW winds along Oregon Coast.

Salem's sounding was saturated to about 7000 feet and dry above. Medford's sounding was saturated from 5000-7000 feet and dry above and below. Salem's sounding was neutral below about 7000 feet and stable above and Medford's sounding was stable throughout.

The pressure gradient across the Cascades increased through the day which resulted in light southeast winds through the morning becoming light to moderate westerlies by 1700 PST.

DATE: 7/27/91. One fire ignited (Burn code NIAG5) on the Siskiyou National Forest.

700 mb level: moderate westerlies prevailed with weaker westerlies in southern Oregon.
850 mb level: A complex pattern existed over Oregon; however, light variable winds generally occurred over the southern Willamette Valley, with NNW to NE winds further south.

The Salem sounding was saturated to about 1800 feet and dry above. The Medford sounding was dry throughout. Both soundings were stable.

This is the only fire for testing PUFF in the Coast Range.

PLUME OBSERVATIONS FOR TEST FIRES

The 15 fires used in this analysis are denoted in the second column of table 1 by a ">" character. Of these, only four were burned under unstable airmass conditions; all four were on the Wenatchee. Size of burn ranged from 8 acres (SUN2) to 51 acres (ASTRO3). Total woody and duff fuel loading ranged from 54 tons per acre (FLY1) to 151.1 tons per acre (UPC8).

Fire Specific Data

All relevant data for each of the 15 fires is presented in the tables and figures in Appendix A. Unit information includes location, date, elevation, acres, loading, and 1000hr moisture. Weather data includes stability and upper air windspeed and direction. The observed plume trajectory is plotted with the PUFF-modeled trajectory. These plots provide a visual assessment of the model's performance for each of the fires. Accompanying the data for each fire in Appendix A are plots from the PUFF runs, including EPM output, planimetric views of the modeled trajectory, and elevation views of the trajectory and modeled concentrations (These last two figures contain the data with which quantitative comparisons to observed data were made.).

Continually changing model algorithms and structure made it difficult to determine when PUFF was stable and ready for assessment. Therefore, we chose to do a qualitative review of PUFF and observed data. The plots presented in the following discussion provide information useful for a qualitative assessment of PUFF. These plots were evaluated by the PUFF Implementation Team and were the basis for the Team's decision to proceed with implementation and field evaluation of PUFF.

Three fundamental aspects of the model's performance were assessed: direction of trajectory (azimuth), distance downwind of plume dispersion (range), and height of the plume top (height). To investigate variance from perfect performance we evaluated each of these three aspects with respect to the maximum height a plume reached and the maximum power produced by each fire. (We hypothesized that increases in either height or power may improve the model's performance.)

Performance--Azimuth

PUFF vs. Observed.-- The azimuth modeled by PUFF is compared with the observed azimuth for 15 fires in figure 1. Three diagonal lines are shown. If a modeled azimuth exactly matches the observed azimuth, the data point falls on the center line. The upper and lower diagonal lines show where PUFF differs from observed by +45 degrees and -45 degrees, respectively. Note that all but three fires were modeled within 45 degrees of the observed azimuth.

Delta Azimuth vs. Height.-- Figure 2 illustrates how observed height relates to the difference in azimuth between PUFF and observed (Delta Azimuth). There is no significance to the relationship.

Delta Azimuth vs. Power.-- Figure 3 illustrates how Delta Azimuth relates to the maximum energy (power) modeled for each burn. No significance was found.

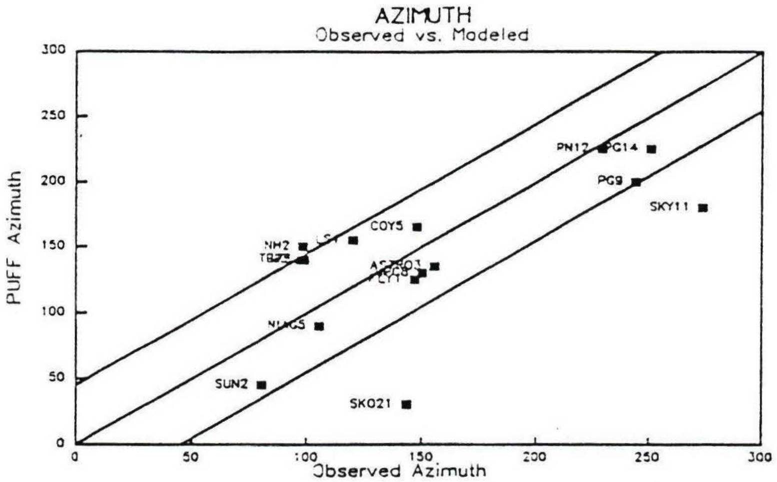


Figure 1. PUFF azimuth vs. observed azimuth for 15 tests.

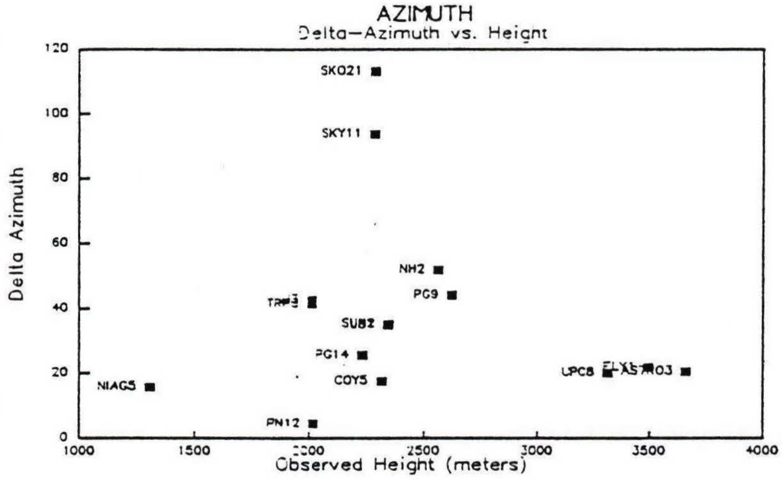


Figure 2. Delta Azimuth vs. observed height for 15 tests.

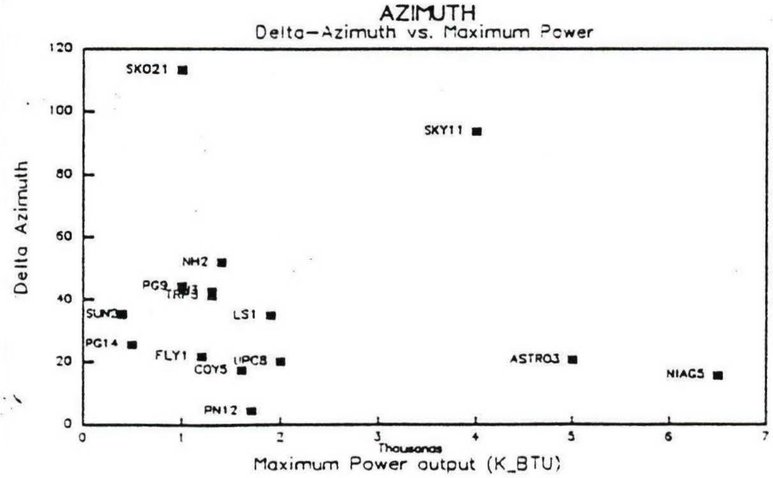


Figure 3. Delta azimuth vs. maximum power for 15 tests.

Performance--Range

PUFF vs. Observed.-- The distance downwind (range) to which PUFF-predicted concentrations of particulate matter became less than 100 micrograms per cubic meter is compared to the observed range in figure 4. The diagonal line shows where a perfect fit would lie, and is not a regression line. Note that PUFF range is higher than observed for all but 2 fires. The observed range is based on ocular estimates using observed opacity of the smoke plume edges and downwind tail. Both pilot and observer concurred, and consistency between burns was maintained as much as possible. The tail and edges of smoke plumes remains in surprising integrity for many miles downwind, with relatively distinct contrast to adjacent background air.

Delta Range vs. Height.-- In figure 2, the difference in range between PUFF and observed appears to increase with increases in observed plume height. However, no significance was found to the relationship.

Delta Range vs. Power.-- No significance was found to the relationship between Delta Range and maximum power of the fire (figure 6).

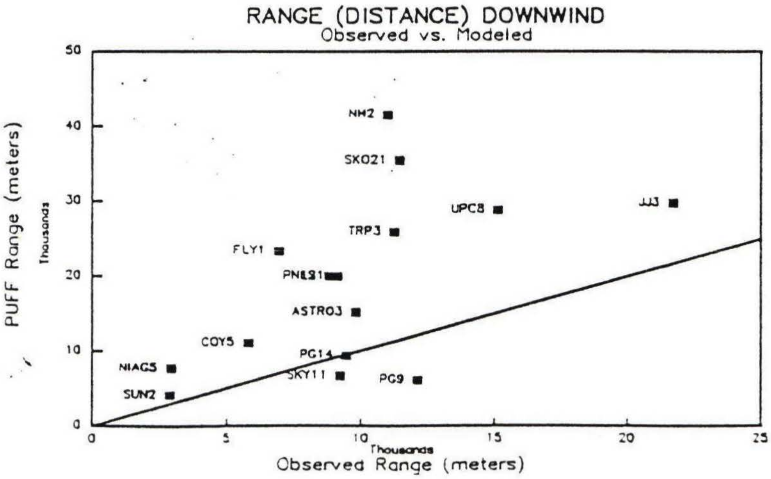


Figure 4. PUFF range vs. observed range for 15 tests.

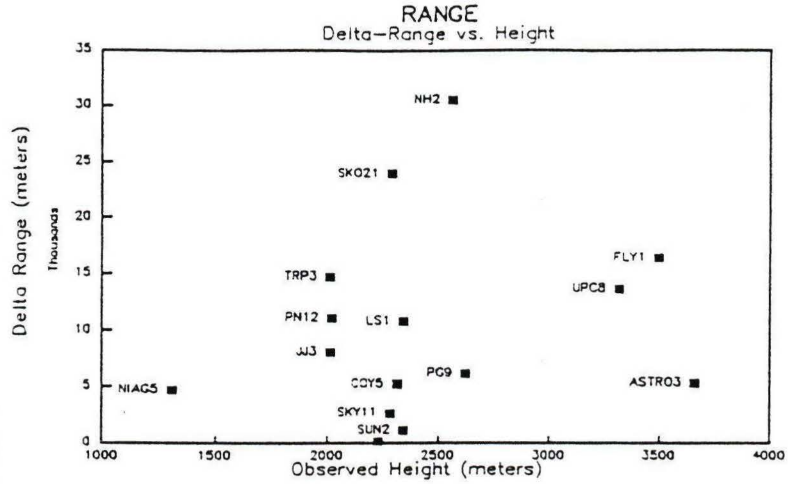


Figure 5. Delta Range vs. observed height for 15 tests.

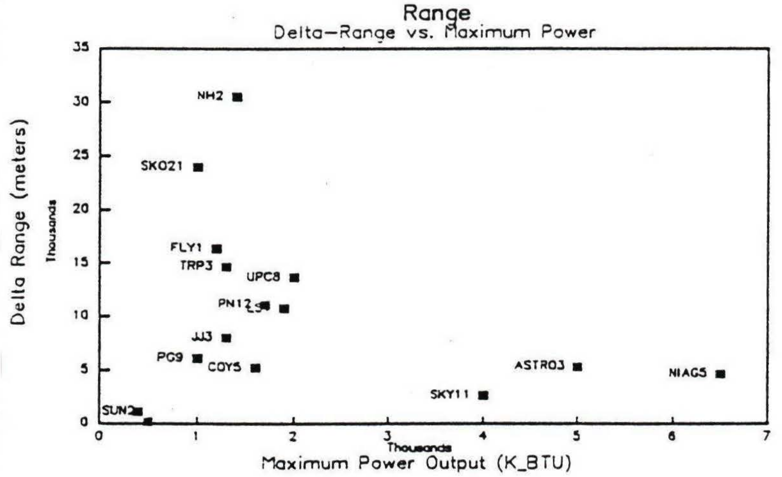


Figure 6. Delta Range vs, maximum power for 15 tests.

Performance--Height

PUFF vs. Observed.-- The tendency of PUFF to underestimate the height of the smoke plume is illustrated in figure 7. The diagonal line indicates where a perfect fit would lie, and is not a regression line.

Delta Height vs. Power.-- There is no significance to the relationship between Delta Height and maximum power, as shown in figure 8.

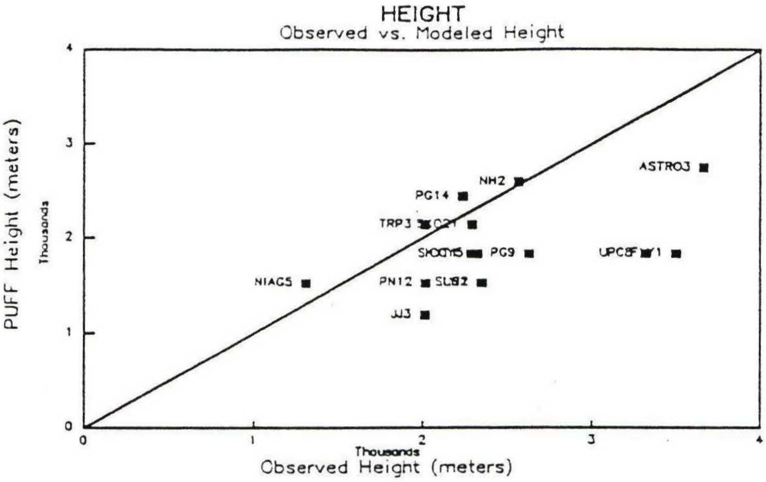


Figure 7. PUFF height vs. observed height for 15 tests.

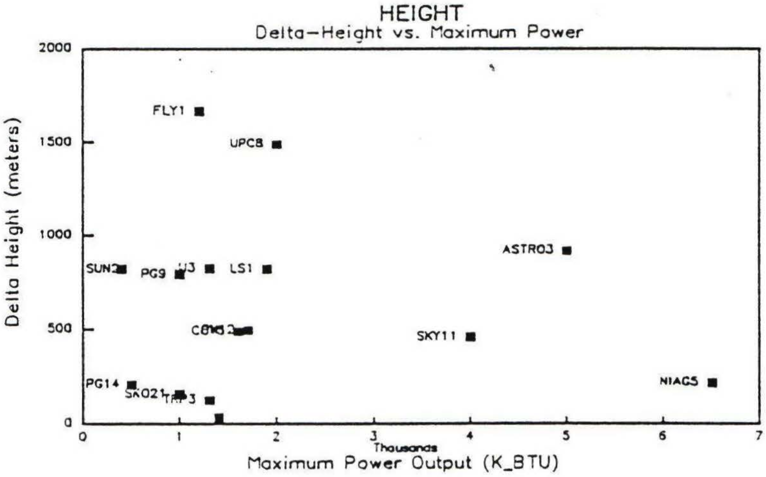


Figure 8. Delta Height vs. maximum power for 15 tests.

DISCUSSION

Surface and Upper Level Winds

PUFF uses the National Weather Service's Nested Grid Model (NGM) 850 mb and 700 mb level wind data to produce its' upper level wind field. The NGM data grid interval is 1.25 degrees latitude by 2.5 degrees longitude and each NGM file contains observation data for the analysis time (either 0400 PST or 1600 PST) and for forecasts at 6 hour intervals thereafter. PUFF interpolates linearly over both space and time to develop a three dimensional windfield between the 850 and 700 mb levels that evolves with time. (850 mb is about 5,000' msl; 700 mb is about 9,000' msl). Although the documentation does not mention what happens to the upper level winds above the 700 mb level, and no mention is made of continuing the linear extrapolation that is applied between the 850 and 700 mb level, it is assumed that the winds are held constant at the 700 mb values.

Instead of using the NGM data, it is possible to instead enter a single 850 mb level wind speed and direction, in which case, the upper level wind field is held constant throughout the model run.

To determine a surface wind field, two options are again possible. The operator may either explicitly enter a single wind direction and speed, or PUFF's default algorithm will calculate the surface wind. In either case, the surface wind is calculated once, and is held constant through the model simulation. PUFF's default algorithm extrapolates the analysis time 850 mb level winds to the surface to produce a first guess surface wind field. PUFF then adjusts these winds the minimum amount necessary to conserve mass. (It is assumed that the near surface vertical velocity must be zero.) These adjustments apparently turn the surface winds parallel to the topographic contours.

Performance Based on Meteorological Considerations

The following discussion considers the ramifications of PUFF's modeling approach, and is based on considerations of PUFF's exploitation of NGM-scale weather data, rather than on a rigorous analysis of PUFF's results against observations. Some general comments are made about how PUFF may perform in different situations and when PUFF would be expected to do best and least well.

The "upper level" winds are taken directly from the NGM model. This is an excellent forecast model for the synoptic scale, meaning weather features may be resolved on the order of a few hundred kilometers. It was not designed to forecast weather on a smaller scale. The model terrain rises from the Pacific Ocean to the Rockies and does not independently resolve the Olympics, Coast Range, or the Cascades (see figure 9).

If the NGM model run verifies accurately (which it often but not always does), and the smoke plume from a relatively low elevation fire surrounded by low elevation terrain (i.e., significantly below 5,000 feet msl) rises into the free air flow (i.e., the winds above the 850 mb level, so above 5,000 feet msl) then PUFF should perform well. In this case, PUFF is primarily a tool to help visualize how the NGM winds will carry the smoke with time. (PUFF's displays are impressive). It is uncertain how well PUFF will do with high elevation burns that are surrounded by higher elevation complex terrain, especially those burns with insufficient energy for the plumes to rise substantially or during smoldering stages. If the terrain is above the elevation of the 850 mb level (about 5,000 feet msl) then presumably, PUFF will model the surface winds as if they were free air winds.

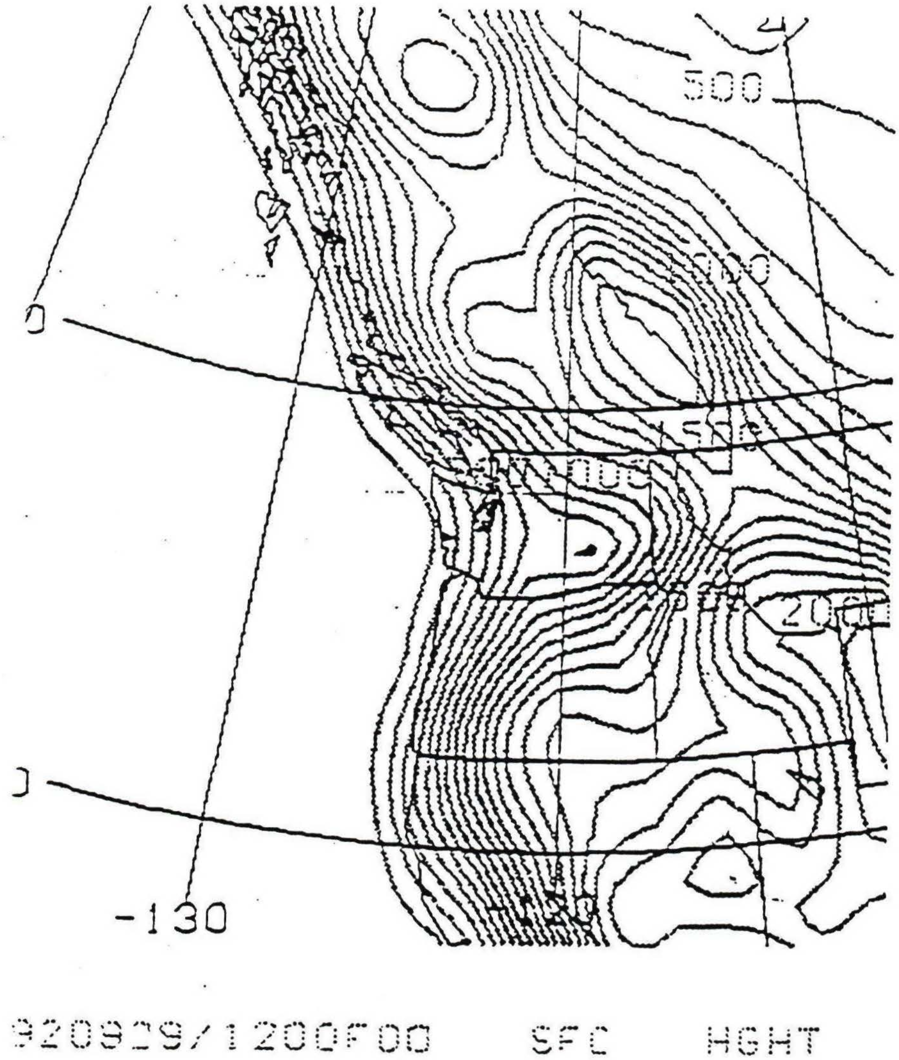


Figure 9. The NGM data uses digital terrain that does not independently resolve the Olympics, Coast Range, or the Cascades. The contour interval is 100 meters.

At the time of this assessment, PUFF's method of modeling surface winds is unclear and, perhaps, unrealistic. Two papers provided (by WYNDsoft) in Appendix A of the User's Manual were evaluated for this discussion. The algorithm used was apparently developed by Barnard, Wegley and Heister to forecast wind speed and directions on a small scale (4 km square) when several observations within the area existed and further detailed wind data was required. Their model performed well in all but light wind cases; however, it is important to keep in mind that their "first guess" wind field contained several accurate values. Apparently, WYNDsoft hopes in the future to fit PUFF's surface wind field to actual observations. However, for present, Puff's "first guess" wind field is derived by interpolating the 850 mb flow to the ground. This is unrealistic when the surface flow is decoupled from the 850 mb level flow, as often happens with valley or slope winds or in passes where temperature gradients or pressure gradients combine with topographic constraints to force the surface flow. The model surface winds and initial state surface observations during the 6 model verification days were generally light, so it is difficult to give specific analyses.

However, the user must be aware that the model surface winds are calculated at NGM analysis time only (either 0400 PST or 1600 PST) and are held constant throughout the simulation. As an example, on 6/19/91, Stampede Pass recorded calm winds at 0500 PDT and became southwest (230 degrees) at 9 with gusts to 16 by 1700 PDT. If a burn is expected to be ignited in the afternoon, or if there is concern for lingering smoldering smoke from an earlier burn, it may be most appropriate to use NGM data from afternoon observations (the previous day). If the 0Z NGM run is used, the modeled data will have been initialized from 5 PM observations. Therefore, surface winds will be derived from the 850 mb afternoon winds instead of from the morning run. If it becomes apparent that surface winds presented by PUFF for a specific project are significantly different than experience or local evidence suggests, then the user should override the surface wind calculations by entering a uder-defined wind.

NGM Analysis Times

Table 2, below, presents local analysis times for 0Z and 12Z NGM runs, with respective times for Pacific and Mountain time zones. The user must also know that preparation, analysis, and delivery of an NGM run takes 3-4 hours after the initial time. For example, a 0Z run is initialized at 1700 PDT, but may not be available until around 2100 PDT. A 12Z run, initialized at 0500 PDT, should be available around 0900, PDT.

	Local Time			
GMT	PST	PDT	MST	MDT
	- - - (offset hours/local time) - - -			
0Z*	-8/1600	-7/1700	-7/1700	-6/1800
12Z	-8/0400	-7/0500	-7/0500	-6/0600

* Local times for 0Z are the previous day.

CONCLUSIONS

PUFF is far superior to any previous attempt at PC-based modeling of smoke dispersion from prescribed broadcast burning. The user interface is exceptional. PUFF's organization and display of relevant weather data is as good as many commercial weather product vendors. Users of PUFF will enjoy the visual feedback and gaming potential of PUFF.

The model appears to be relatively stable at the present time. While WYNDsoft has had significant difficulty in debugging, error handling, and testing of PUFF, the contractor has demonstrated a commitment to make the product usable and robust. PNW has received numerous repairs since formal delivery of the product. We expect this may continue, and recommend that the implementation team handle any future changes deliberately and that strict version control protocols be followed.

Modeling of surface winds is only of limited success. The effects of terrain are negligible. We note that the words "complex terrain" have been deleted by the contractor from the title. Any burn initiated above the 850mb level (about 5,000') will be dominated by the free-air winds, and little, if no, effect will be realized from surface flow modeling. This is relevant to most of the interior west. WYNDsoft is presently developing improved surface flow modeling.

The scientific documentaton for algorithms is provided in the user's manual. However, we do not feel it represents present conditions in many cases. The appropriate, relevant scientific documentation should be provided.

Our assessment of the quantitative performance of PUFF was favorable. We have noted that trajectory azimuths fall within 45 degrees for all most all of the observations. Distance downwind was a more difficult parameter to observe, but PUFF agrees within reasonable limits.

With several changes in output files, the model will provide significant support to planning and documentation of burning activities. We encourage the users and implementation team to pursue this use of PUFF.

The user's manual requires more improvements. PNW has integrated WYNDsoft documentation with detailed instructions and examples of EPM. We will work with the implementation team to improve and update this document.

We recommend adoption, field testing, and further development of PUFF.

APPENDIX A

Two pages of figures and data are presented in Appendix A for each test fire used in the analysis. The first page contains relevant information regarding the burn unit, weather, and plume observations. The PUFF trajectory and range are plotted with observed trajectory and range. The second page presents three plots from PUFF: The top plot is generated from EPM; PUFF outputs giving planimetric and elevation views are presented in the middle and bottom plots, respectively.

PG9

Unit Information

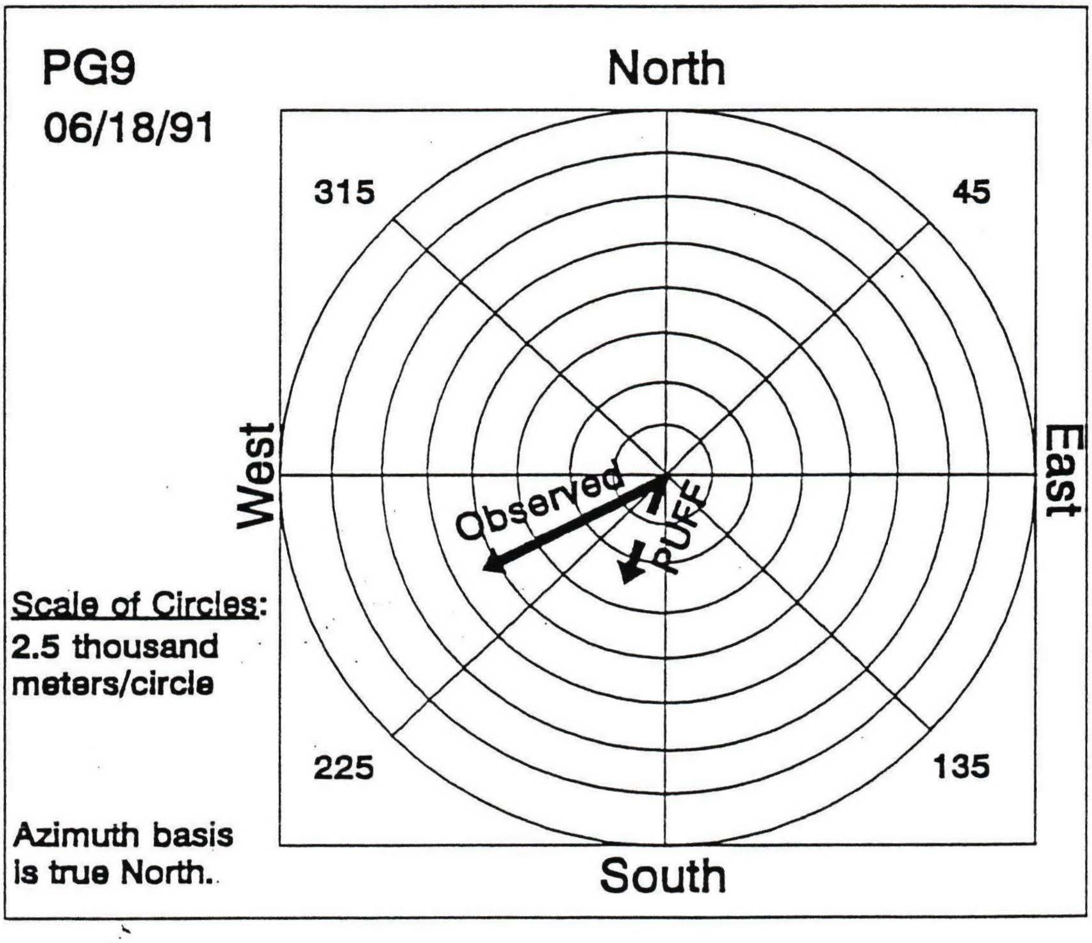
Nat'l. Forest: Wenatchee
Burn Date: 06/18/91
Elevation: 5280' msl
Acres Burned: 29
Total Loading: 62.1 t/a
1000hr Moisture: 30%

Weather Information

Upper Air --
Stability: Unstable
Windspeed: Moderate
Wind Direction: from west

Surface ----
Windspeed: 2 mph

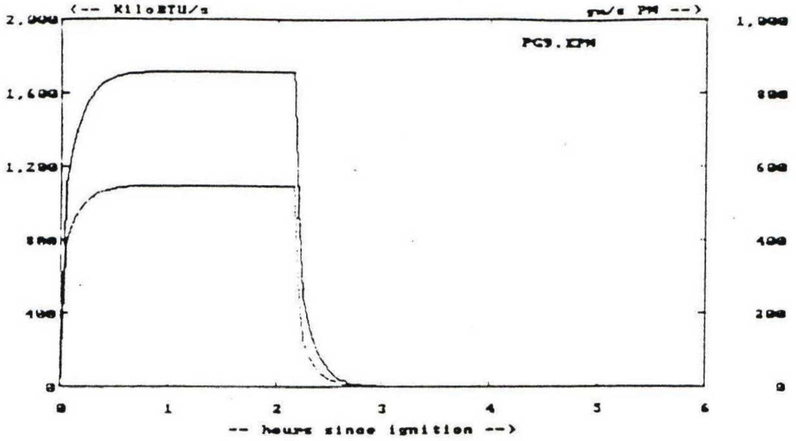
Observed Plume Data
Azimuth: 244
Range: 12,119 meters
Height: 2,620 meters, (8596')

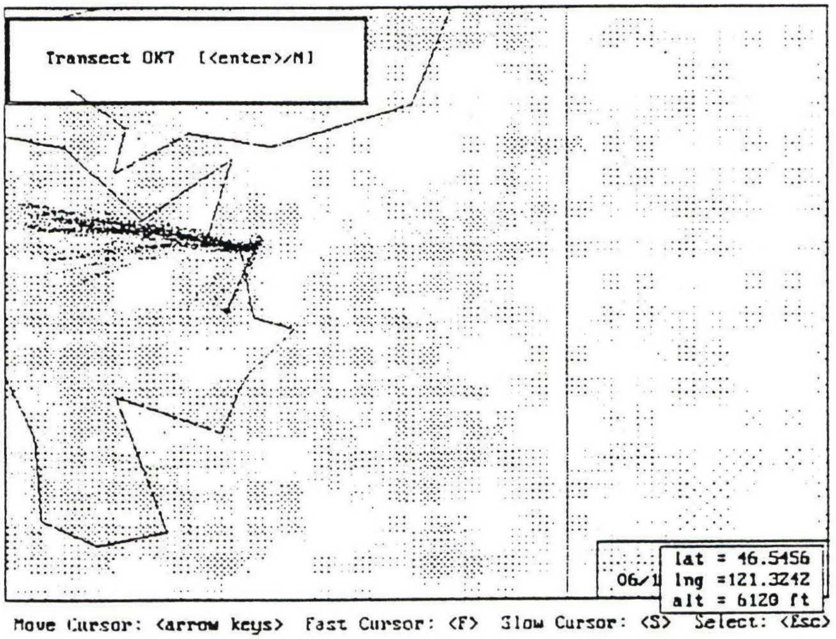


Scale of Circles:
2.5 thousand meters/circle

Azimuth basis is true North..

The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 2.5 thousand meters.

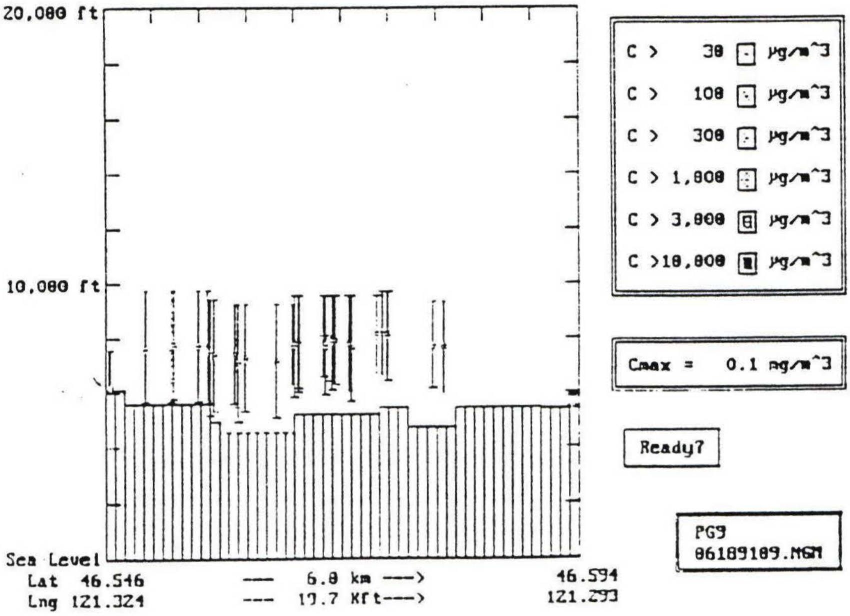



Transect OK? [<enter>/M]

06/1

lat = 46.5456
lng =121.3242
alt = 6120 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



C > 30 ☐ μg/m^3
C > 100 ☐ μg/m^3
C > 300 ☐ μg/m^3
C > 1,000 ▨ μg/m^3
C > 3,000 ▨ μg/m^3
C >10,000 ■ μg/m^3

Cmax = 0.1 mg/m^3

Ready?

PG9
06109109.MGM

PG14

Unit Information

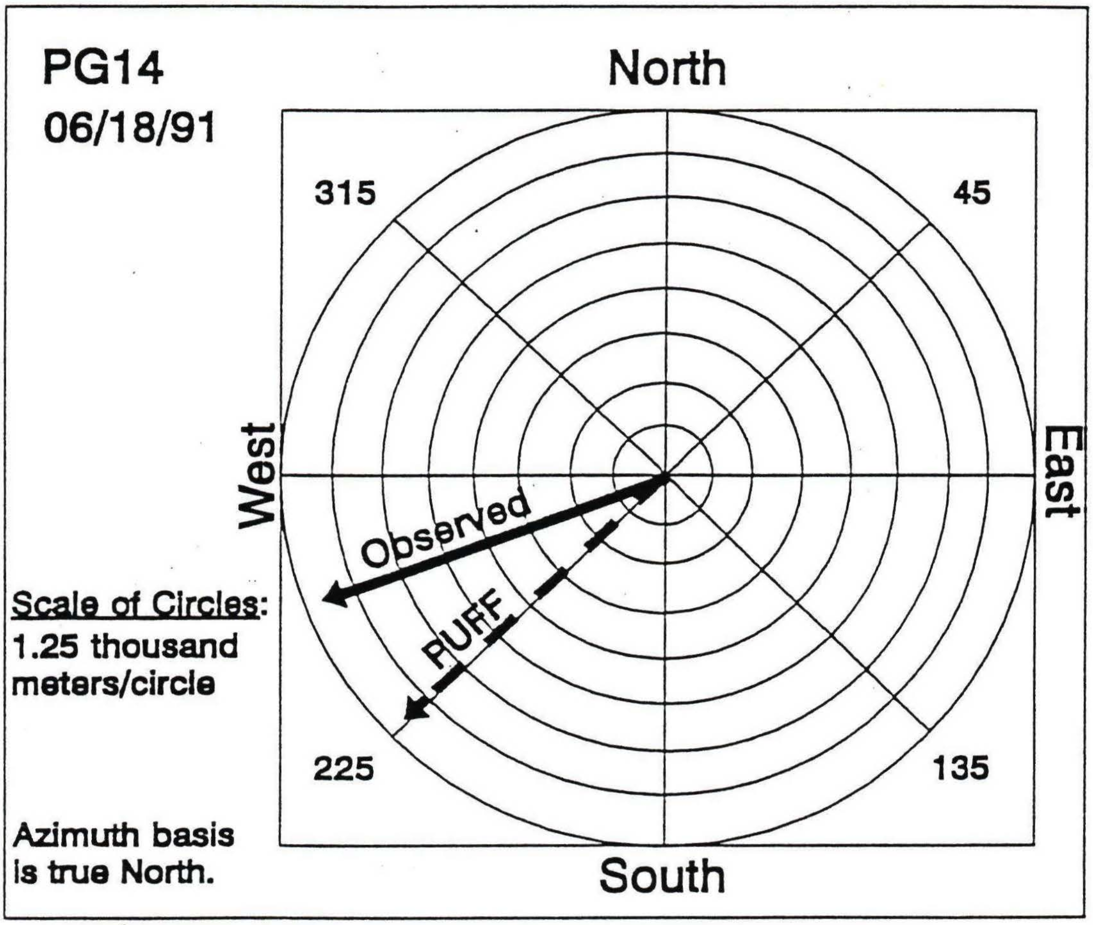
Nat'l. Forest: Wenatchee
Burn Date: 06/18/91
Elevation: 5280' MSL
Acres Burned: 13
Total Loading: 62.1
1000hr Moisture: 30%

Weather Information

Upper Air --
Stability: Unstable
Windspeed: Moderate
Wind Direction: from west

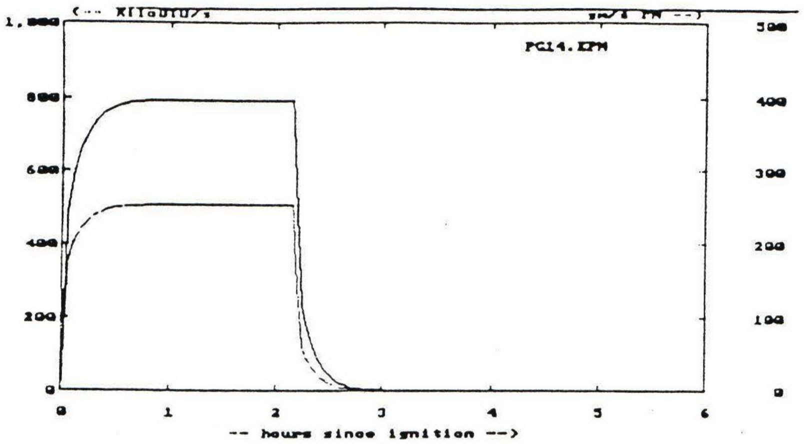
Surface ----
Windspeed: 2 mph

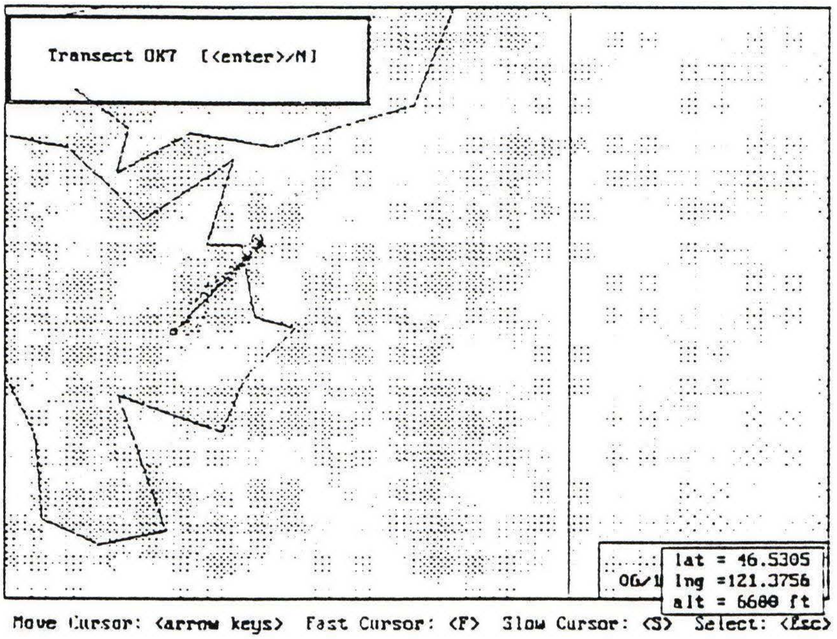
Observed Plume Data
Azimuth: 250
Range: 9,444 meters
Height: 2,232 meters (7,323')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 1.25 thousand meters.

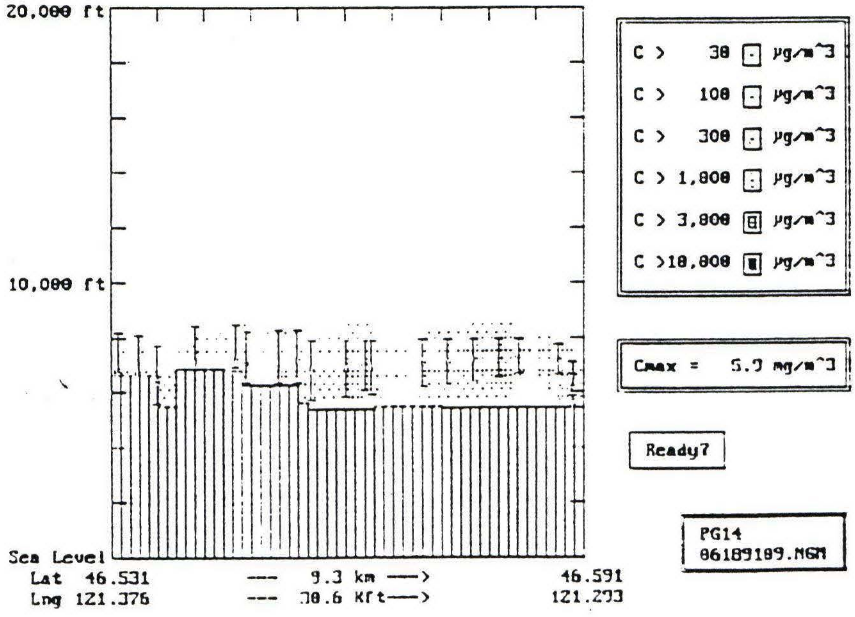
PG14




Transect OK? [<enter>/N]

lat = 46.5305
lng =121.3756
alt = 6600 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



20,000 ft
10,000 ft
Sea Level

C > 30 ⊡ µg/m^3
C > 100 ⊡ µg/m^3
C > 300 ⊡ µg/m^3
C > 1,000 ⊡ µg/m^3
C > 3,000 ▨ µg/m^3
C >10,000 ■ µg/m^3

Cmax = 5.9 mg/m^3

Ready?

PG14
06189109.NGM

Lat 46.531 --- 9.3 km ---> 46.591
Lng 121.376 --- 30.6 Kft---> 121.293

- - Assessment - -

PN12

Unit Information

Nat'l. Forest: Wenatchee
Burn Date: 06/19/91
Elevation: 4600' msl
Acres Burned: 14
Total Loading: 124.9 t/a
1000hr Moisture: 35%

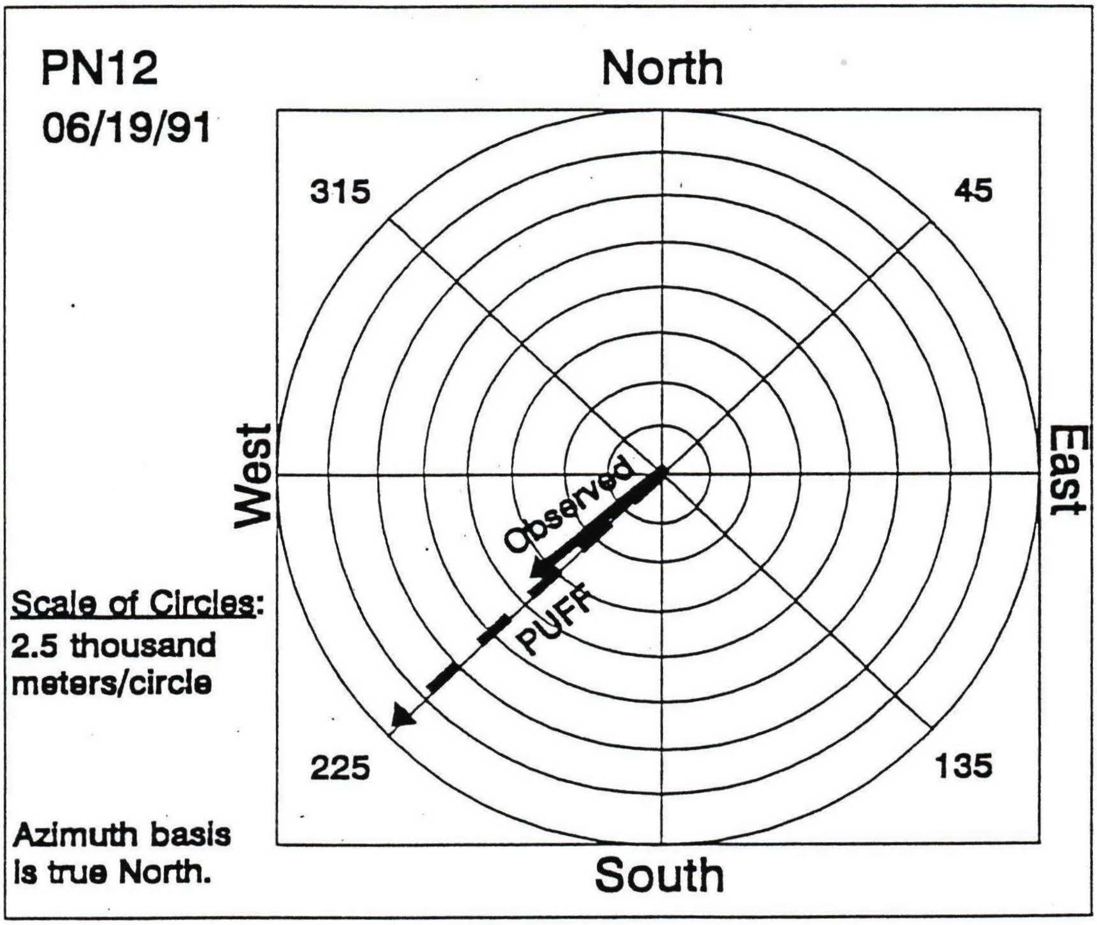
Weather Information

Upper Air --
Stability: Unstable
Windspeed: Moderate
Wind Direction: from west

Surface ----
Windspeed: 4 mph

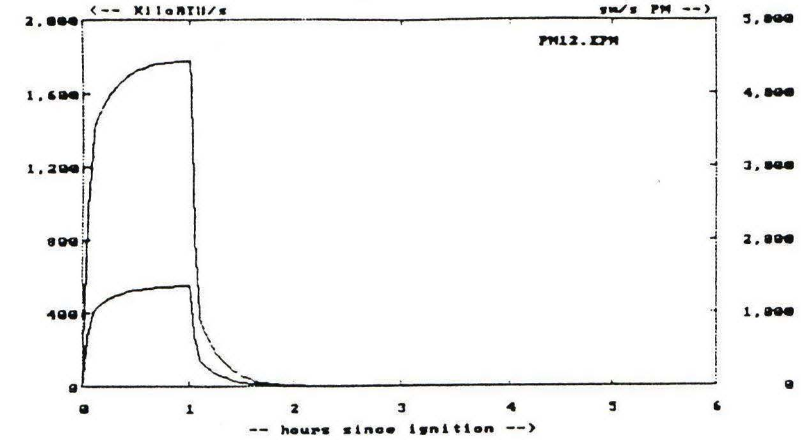
Observed Plume Data

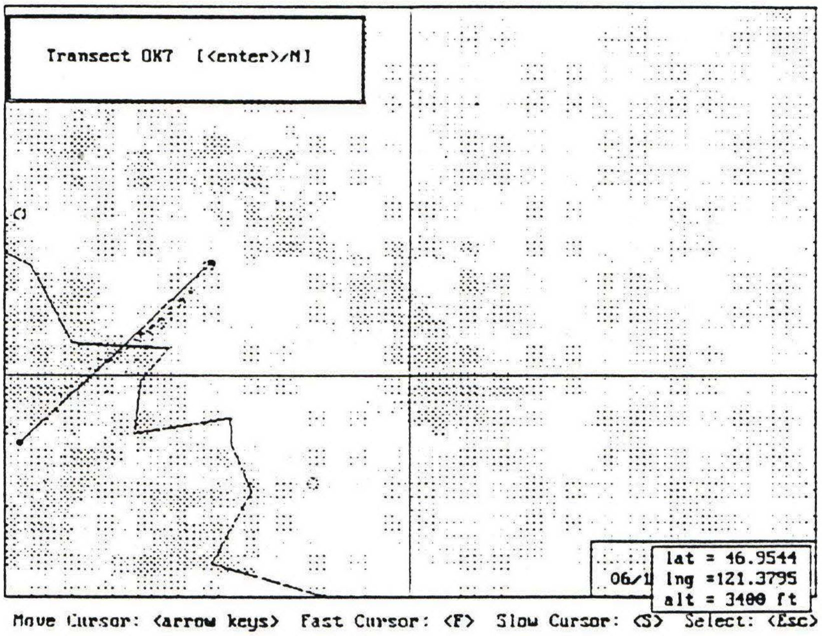
Azimuth: 229
Range: 8820 meters
Height: 2,017 meters (6,618')

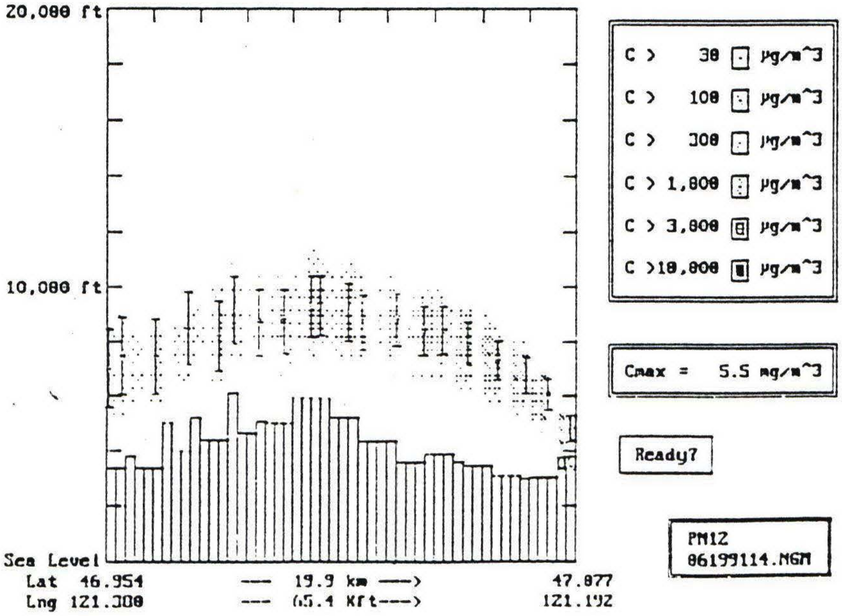


The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 2.5 thousand meters.

PN12


<-- KiloBTU/s
gm/s PM -->
PN12.EPM
2,000
1,600
1,200
800
400
0
5,000
4,000
3,000
2,000
1,000
0
0
1
2
3
4
5
6
-- hours since ignition -->


Transect OK7 [<enter>/M]
lat = 46.9544
lng =121.3795
alt = 3400 ft
06/1
Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>


20,000 ft
10,000 ft
Sea Level
Lat 46.954
Lng 121.308
--- 19.9 km --->
--- 65.4 Kft--->
47.877
121.192
C > 30 μg/m^3
C > 100 μg/m^3
C > 300 μg/m^3
C > 1,000 μg/m^3
C > 3,000 μg/m^3
C >10,000 μg/m^3
Cmax = 5.5 mg/m^3
Ready?
PN12
06199114.NGM

SKY11

Unit Information

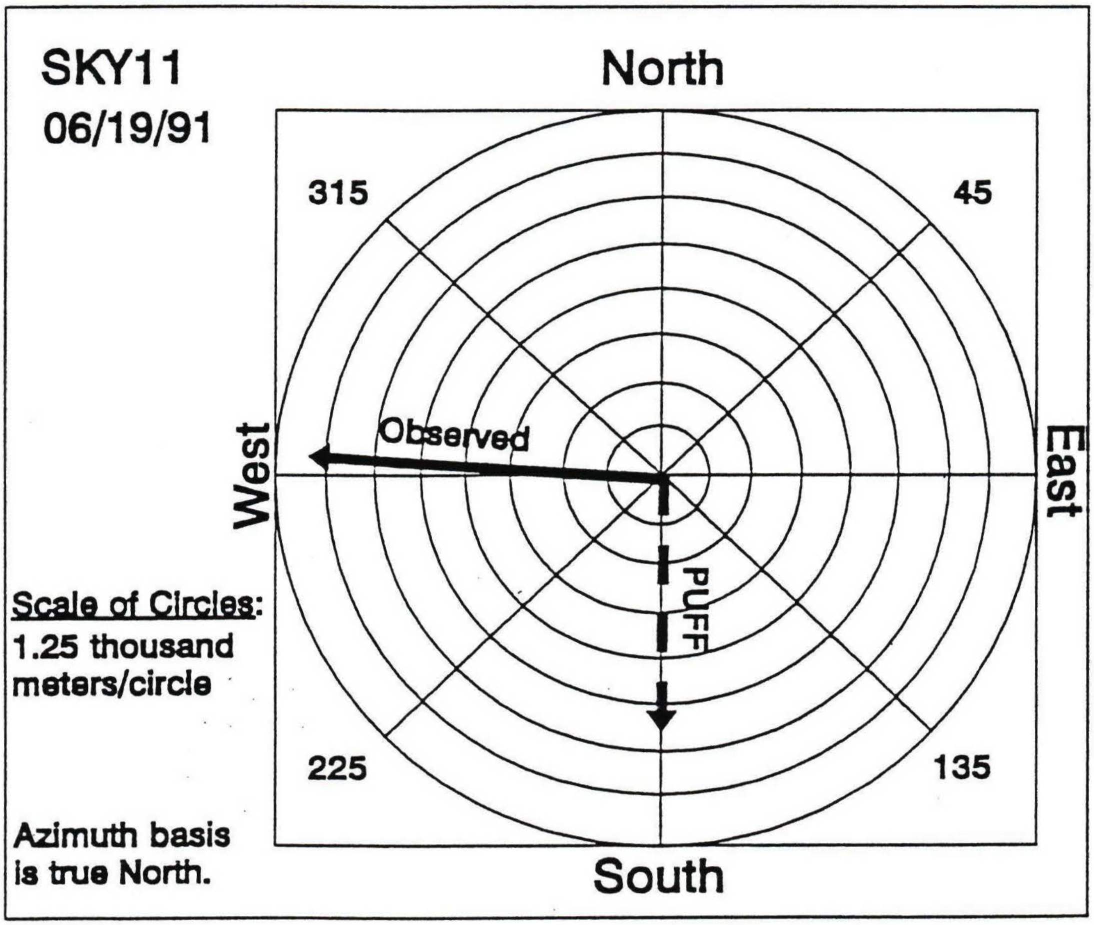
Nat'l. Forest: Wenatchee
Burn Date: 06/19/91
Elevation: 4,000' msl
Acres Burned: 12
Total Loading: 82.6
1000hr Moisture: 25%

Weather Information

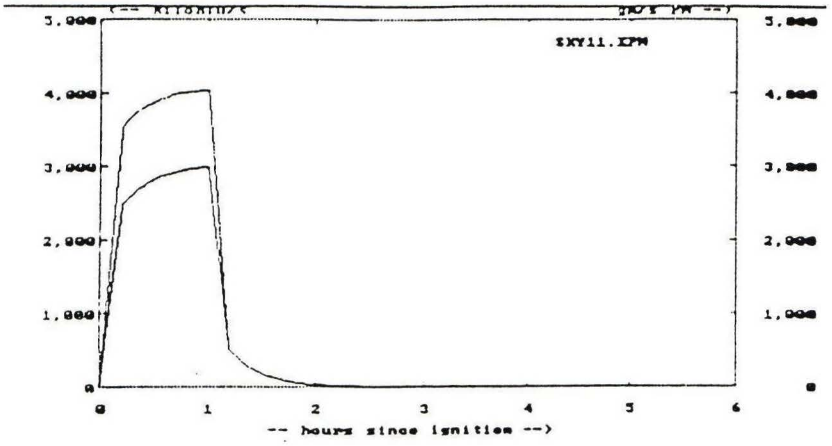
Upper Air --
Stability: Unstable
Windspeed: Moderate
Wind Direction: from west

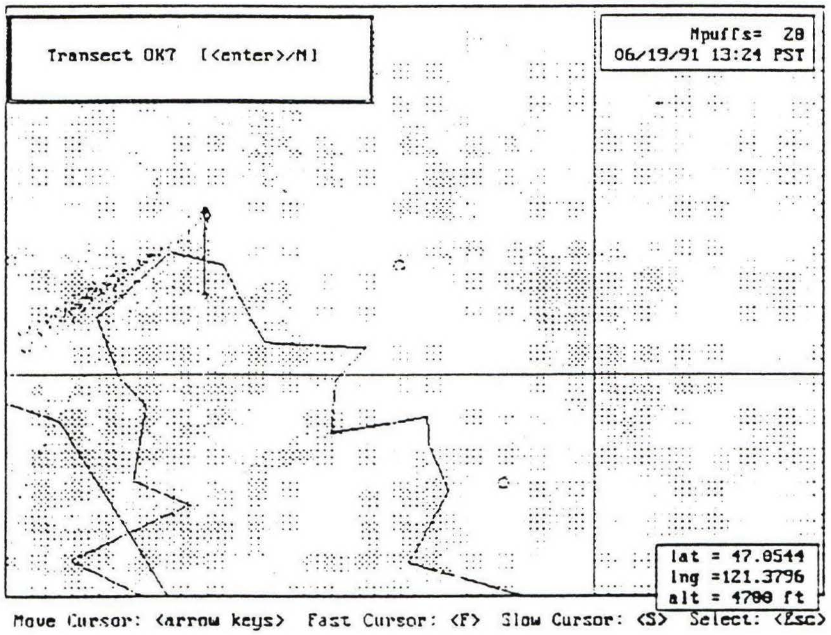
Surface ----
Windspeed: 4 mph

Observed Plume Data
Azimuth: 274
Range: 9,212 meters
Height: 2,285 meters (7,497')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 1.25 thousand meters.

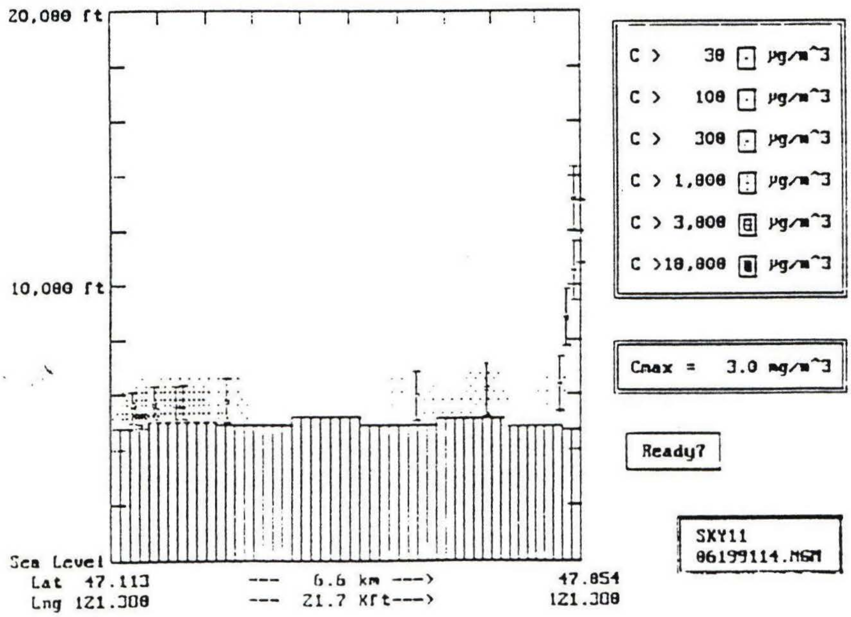




Npuffs= 28
06/19/91 13:24 PST

lat = 47.8544
lng =121.3796
alt = 4700 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



Cmax = 3.0 mg/m^3

SKY11
06199114.MSM

- - Assessment - -

ASTRO3

Unit Information

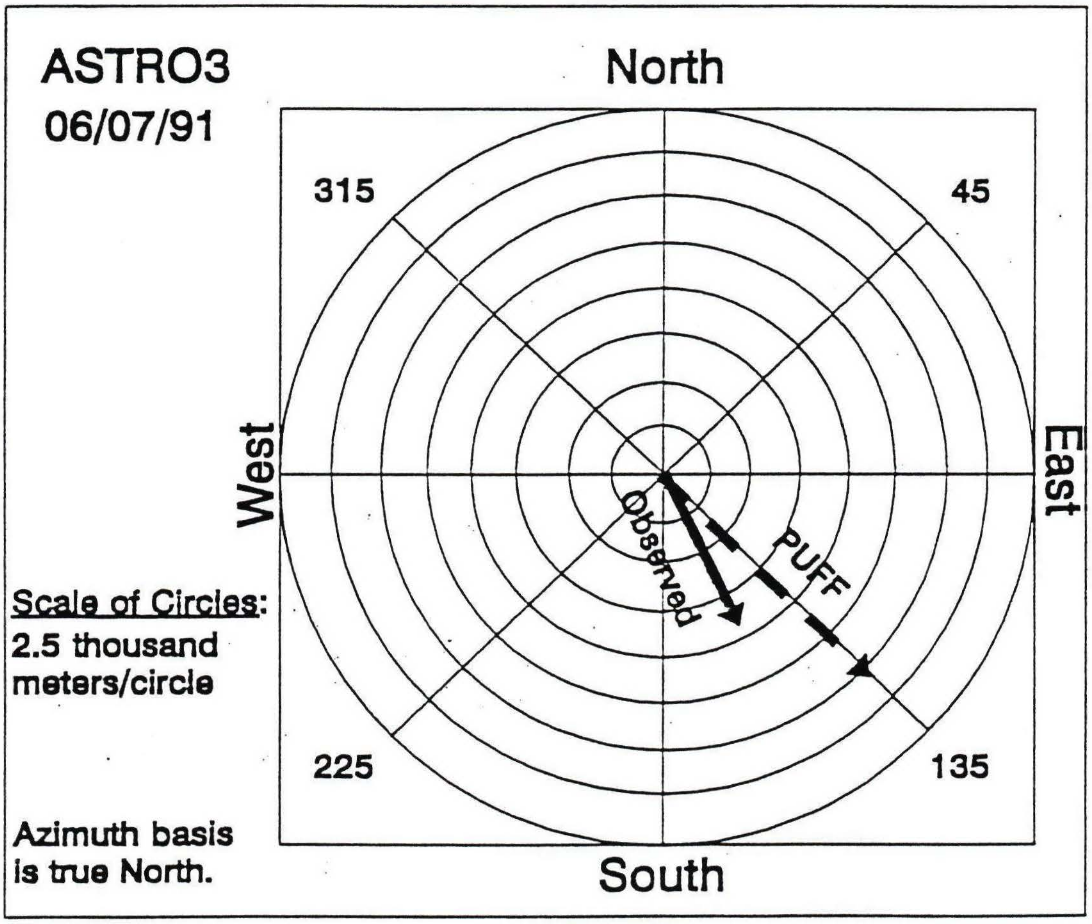
Nat'l. Forest: Willamette
Burn Date: 06/07/91
Elevation: 4060' MSL
Acres Burned: 51
Total Loading: 80.2 t/a
1000hr Moisture: 43%

Weather Information

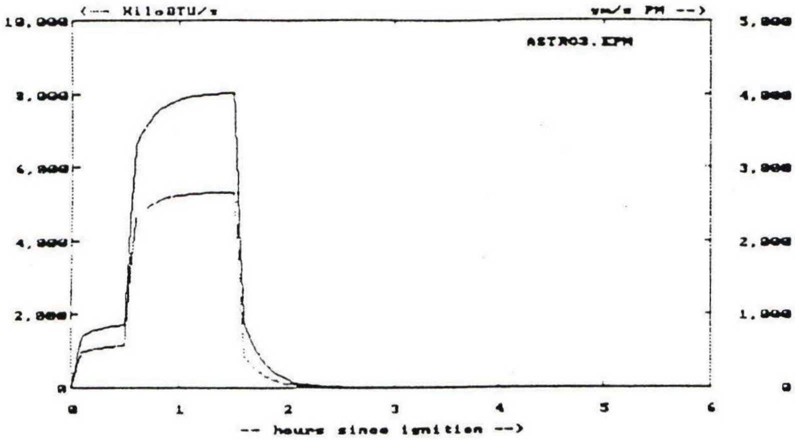
Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

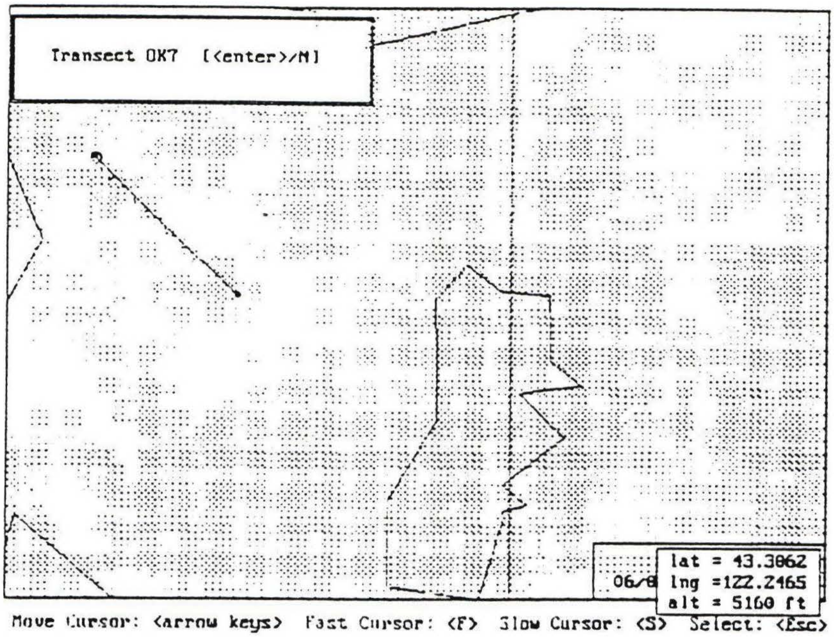
Surface ----
Windspeed: 5 mph

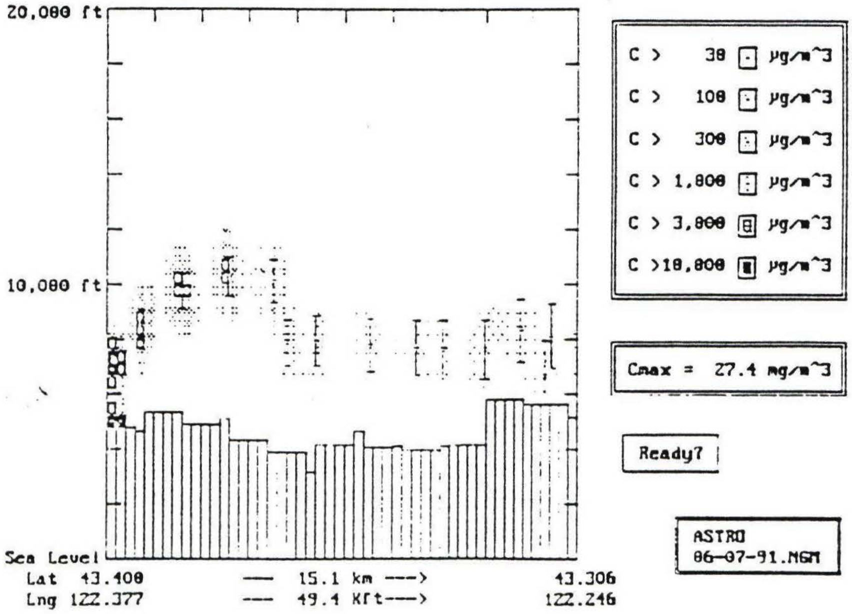
Observed Plume Data
Azimuth: 155
Range: 9,800 meters
Height: 3,657 meters (11,999')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 2.5 thousand meters.


<-- KiloBTU/s
gm/s PM -->
ASTRO3.EPM
10,000
8,000
6,000
4,000
2,000
0
5,000
4,000
3,000
2,000
1,000
0
0
1
2
3
4
5
6
-- hours since ignition -->


Transect OK7 [<enter>/N]
06/0
lat = 43.3862
lng =122.2465
alt = 5160 ft
Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>


20,000 ft
10,000 ft
Sea Level
Lat 43.400
Lng 122.377
15.1 km --->
49.4 Kft--->
43.306
122.246
C > 30 μg/m^3
C > 100 μg/m^3
C > 300 μg/m^3
C > 1,000 μg/m^3
C > 3,000 μg/m^3
C >10,000 μg/m^3
Cmax = 27.4 mg/m^3
Ready7
ASTRO
06-07-91.MGM

UPC8

Unit Information

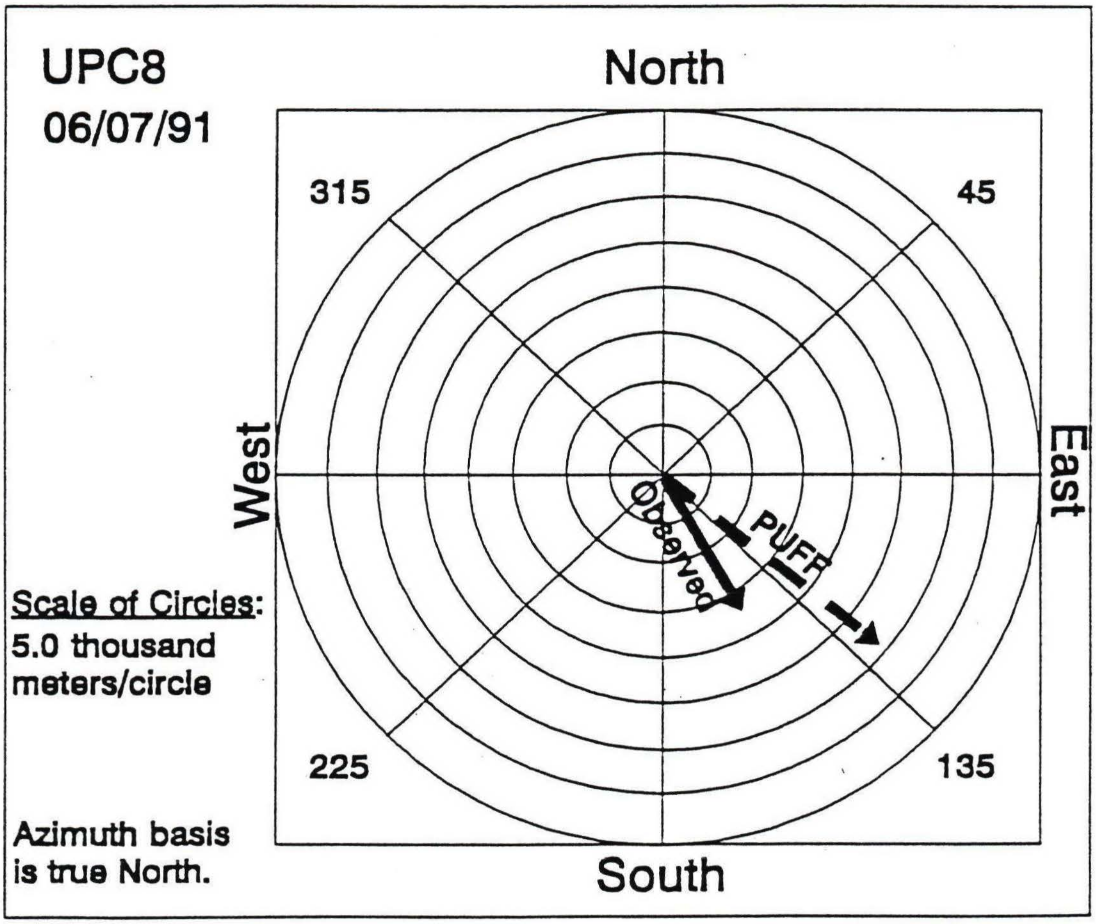
Nat'l. Forest: Willamette
Burn Date: 06/07/91
Elevation: 5,000' MSL
Acres Burned: 16
Total Loading: 151.1 T/A
1000hr Moisture: 20%

Weather Information

Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

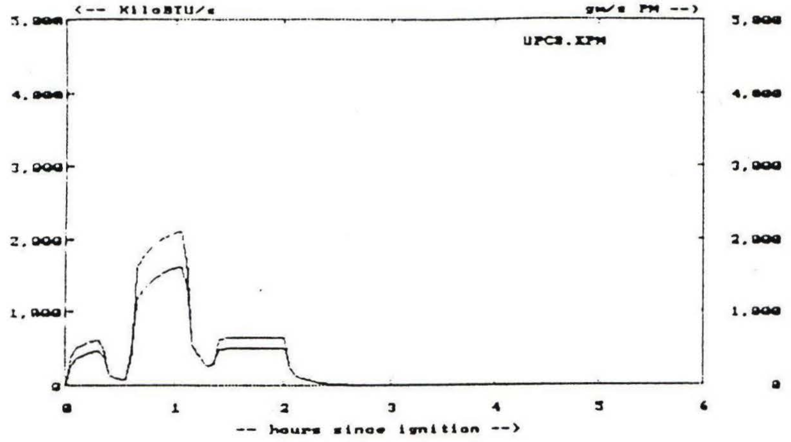
Surface ----
Windspeed: 4 mph

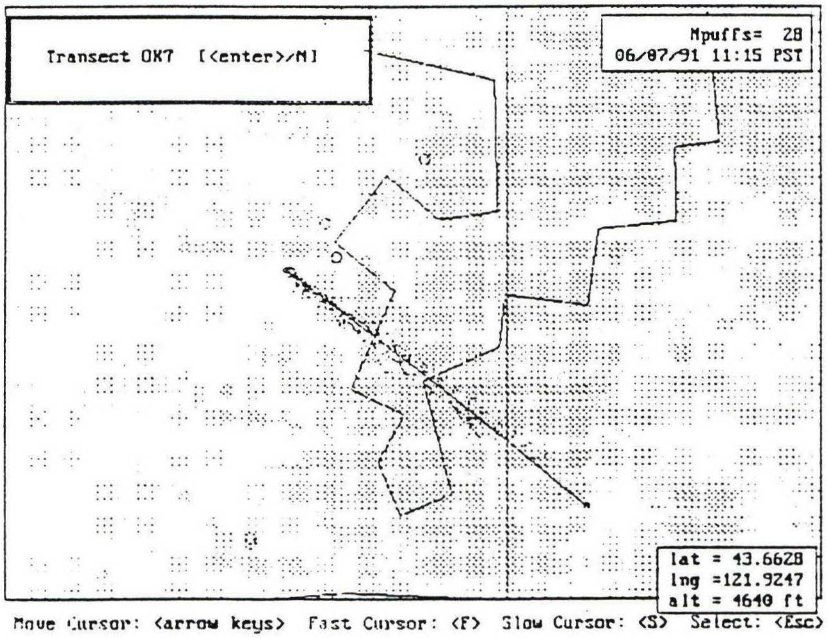
Observed Plume Data
Azimuth: 150
Range: 15,128 meters
Height: 3,317 meters (10,883')


UPC8
06/07/91
North
315
45
West
East
Observed
PUFF
Scale of Circles:
5.0 thousand meters/circle
225
135
Azimuth basis is true North.
South

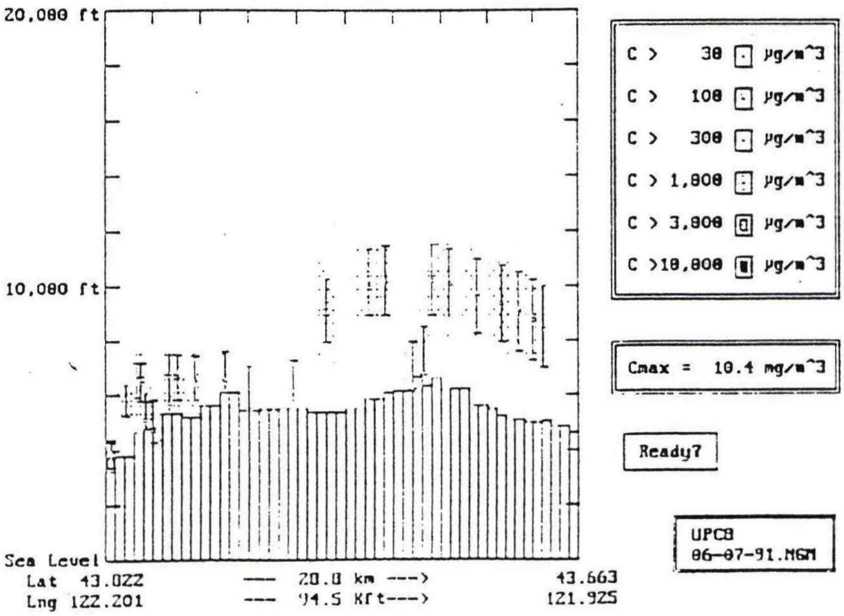
The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 5.0 thousand meters.

UPC8





```
Transect OK7  [<enter>/M]
                                                Npuffs=  28
                                         06/07/91 11:15 PST
                                            lat = 43.6628
                                            lng =121.9247
                                            alt = 4640 ft
Move Cursor: <arrow keys>  Fast Cursor: <F>  Slow Cursor: <S>  Select: <Esc>
```



```
C >     30 ☐ µg/m^3
C >    100 ☐ µg/m^3
C >    300 ☐ µg/m^3
C >  1,000 ☐ µg/m^3
C >  3,000 ▨ µg/m^3
C > 10,000 ■ µg/m^3

Cmax =  10.4 mg/m^3

Ready?

UPC8
06-07-91.MGM

Lat  43.022     ---  20.0 km --->     43.663
Lng 122.201     ---  94.5 Kft--->    121.925
```

- - Assessment - -

FLY1

Unit Information

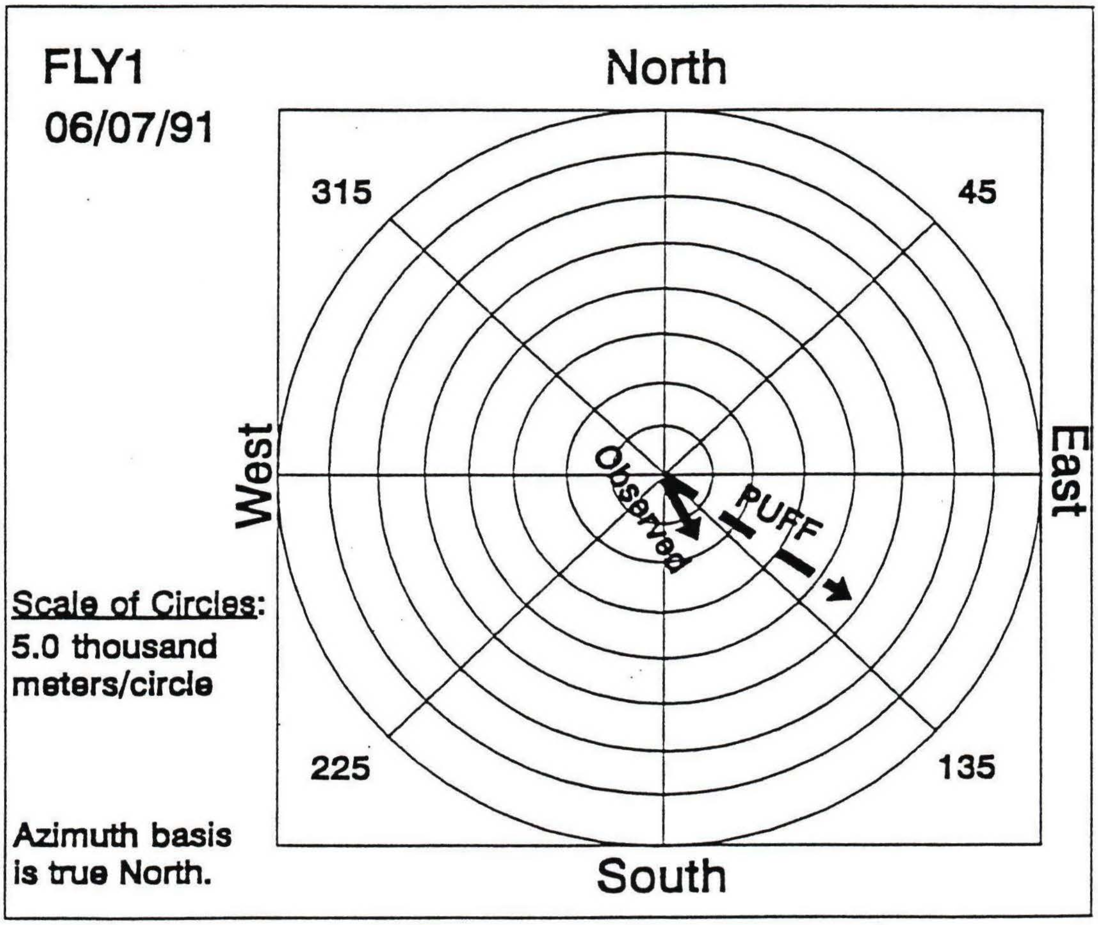
Nat'l. Forest: Willamette
Burn Date: 06/07/91
Elevation: 4,600' MSL
Acres Burned: 10
Total Loading: 54 t/a
1000hr Moisture: 25%

Weather Information

Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

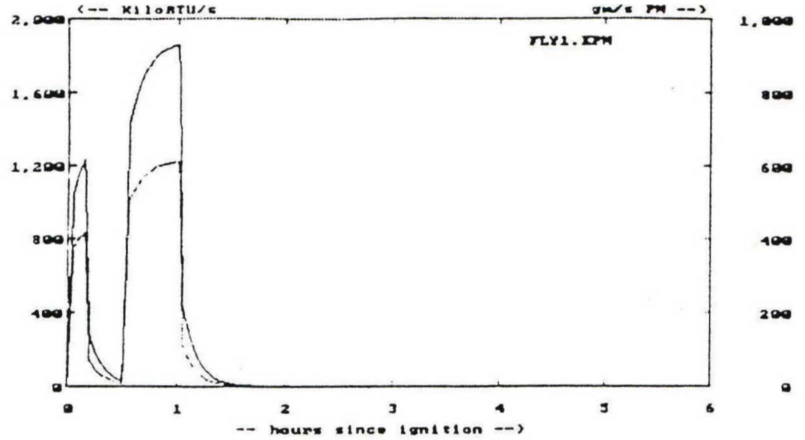
Surface ----
Windspeed: 5 mph

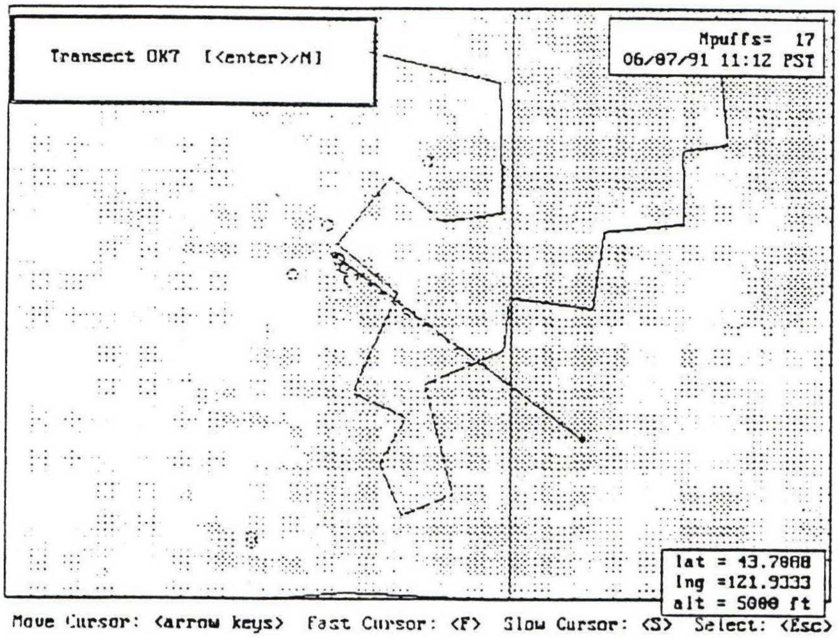
Observed Plume Data
Azimuth: 147
Range: 6,917 meters
Height: 3,494 meters (11,463')

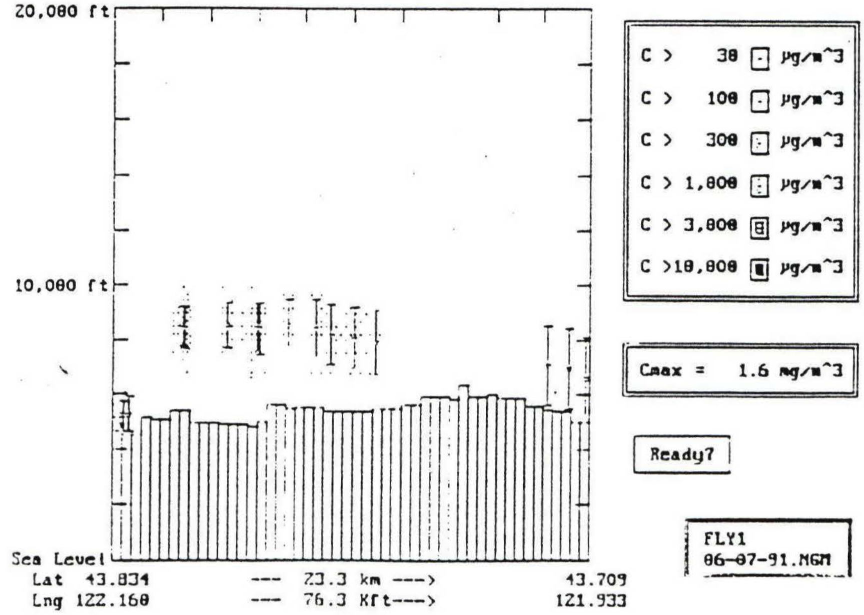


The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 5.0 thousand meters.

FLY1


<-- KiloBTU/s
gm/s PM -->
FLY1.XPM
2,000
1,600
1,200
800
400
0
1,000
800
600
400
200
0
0
1
2
3
4
5
6
-- hours since ignition -->


Transect OK7 [<enter>/N]
Npuffs= 17
06/07/91 11:12 PST
lat = 43.7000
lng =121.9333
alt = 5000 ft
Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>


20,000 ft
10,000 ft
Sea Level
Lat 43.834
--- 23.3 km --->
43.709
Lng 122.160
--- 76.3 Kft--->
121.933
C > 30 μg/m^3
C > 100 μg/m^3
C > 300 μg/m^3
C > 1,000 μg/m^3
C > 3,000 μg/m^3
C >10,000 μg/m^3
Cmax = 1.6 mg/m^3
Ready?
FLY1
06-07-91.MGM

COY5

Unit Information

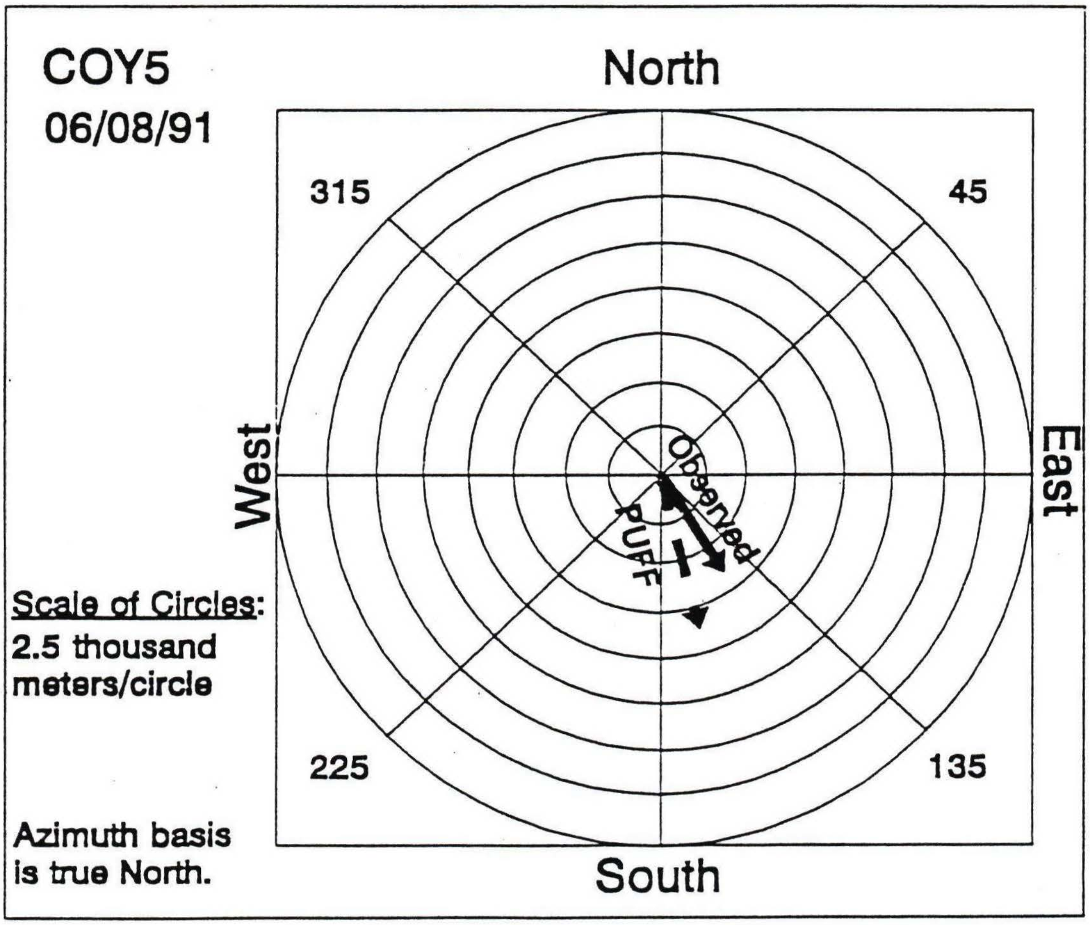
Nat'l. Forest: Willamette
Burn Date: 06/08/91
Elevation: 3,920' msl
Acres Burned: 23
Total Loading: 78.6 t/a
1000hr Moisture: 36%

Weather Information

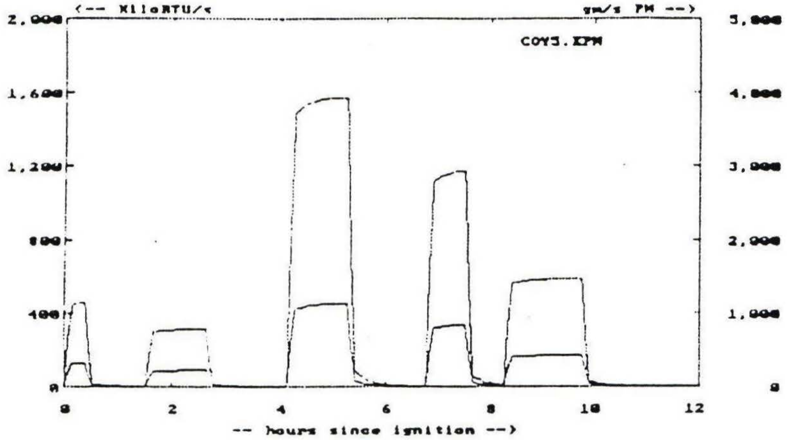
Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

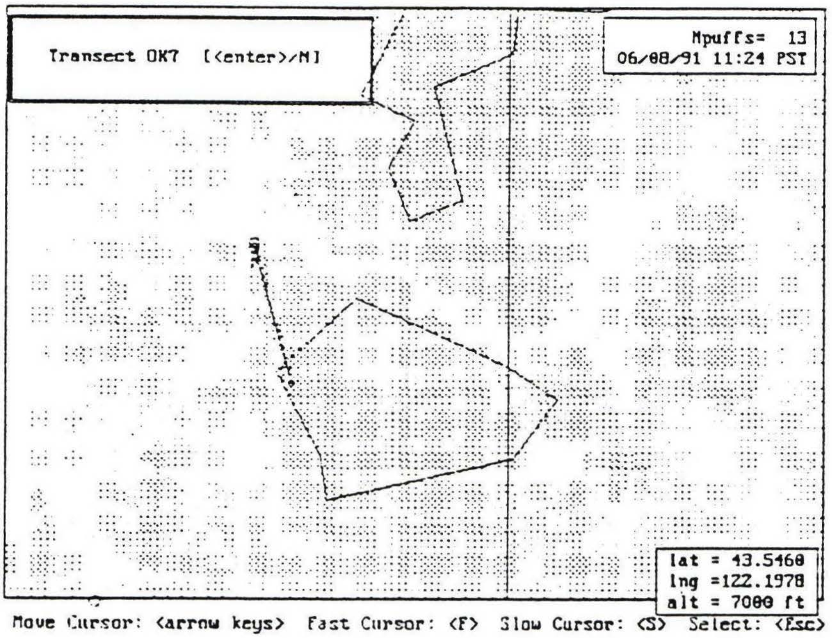
Surface ----
Windspeed: 6 mph

Observed Plume Data
Azimuth: 148
Range: 5,788 meters
Height: 2,316 meters (7,599')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 2.5 thousand meters.

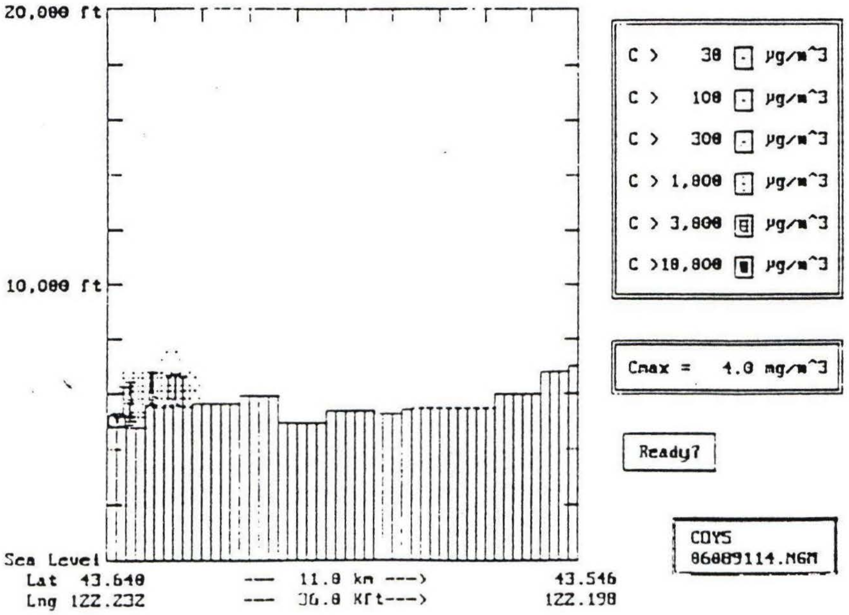



Transect OK7 [<enter>/M]

Npuffs= 13
06/08/91 11:24 PST

lat = 43.5460
lng =122.1978
alt = 7000 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



Cmax = 4.0 mg/m^3

Ready?

COY5
06089114.NGM

LS1

Unit Information

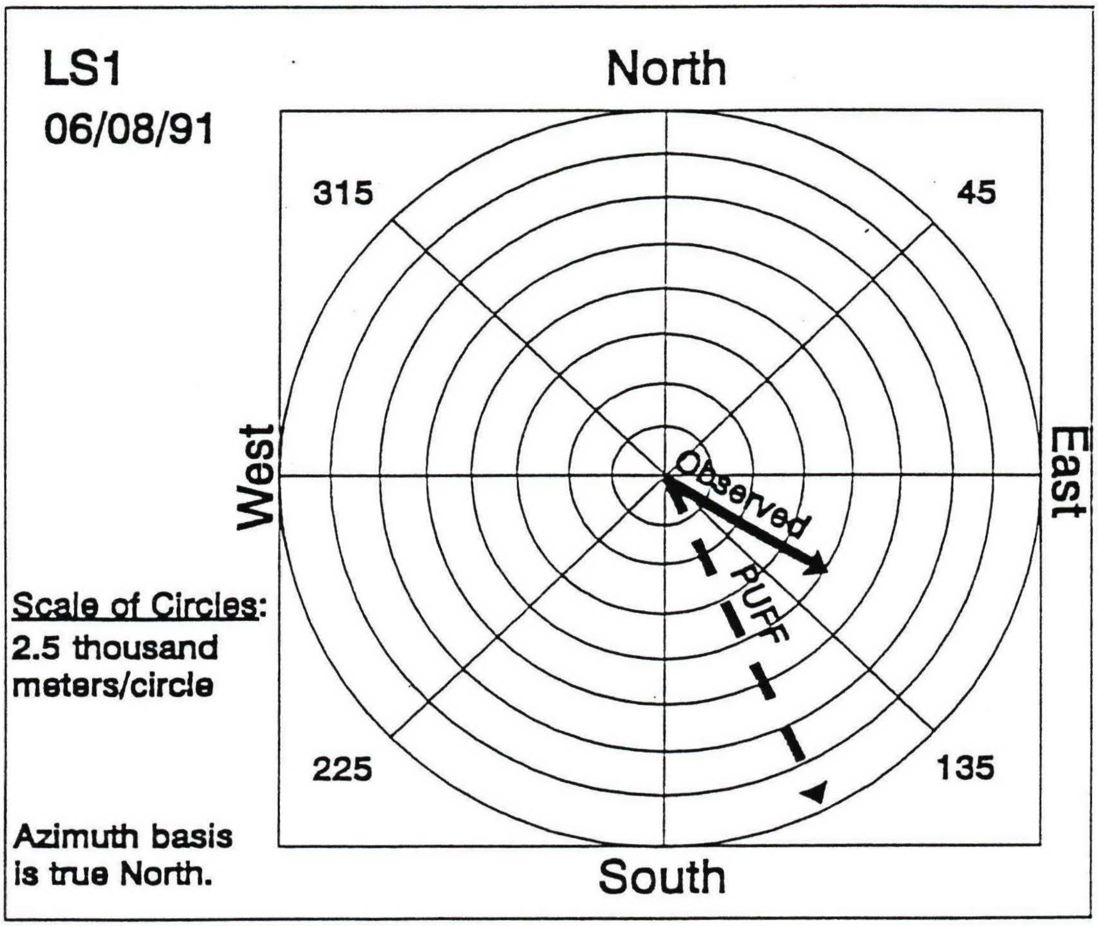
Nat'l. Forest: Willamette
Burn Date: 06/08/91
Elevation: 4,660' msl
Acres Burned: 30
Total Loading: 63.7 t/a
1000hr Moisture: 40%

Weather Information

Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

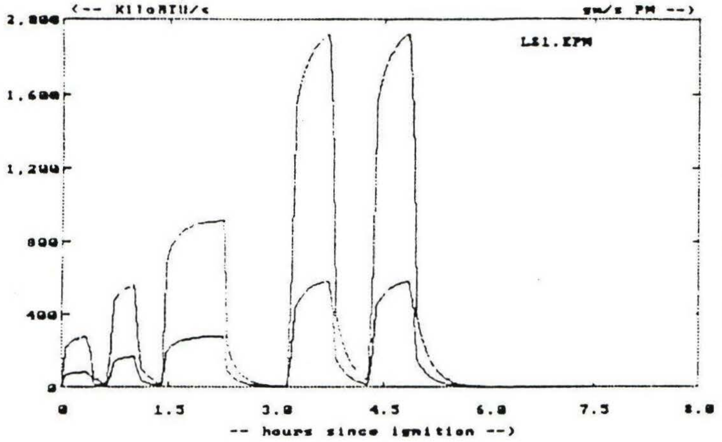
Surface ----
Windspeed: 4 mph

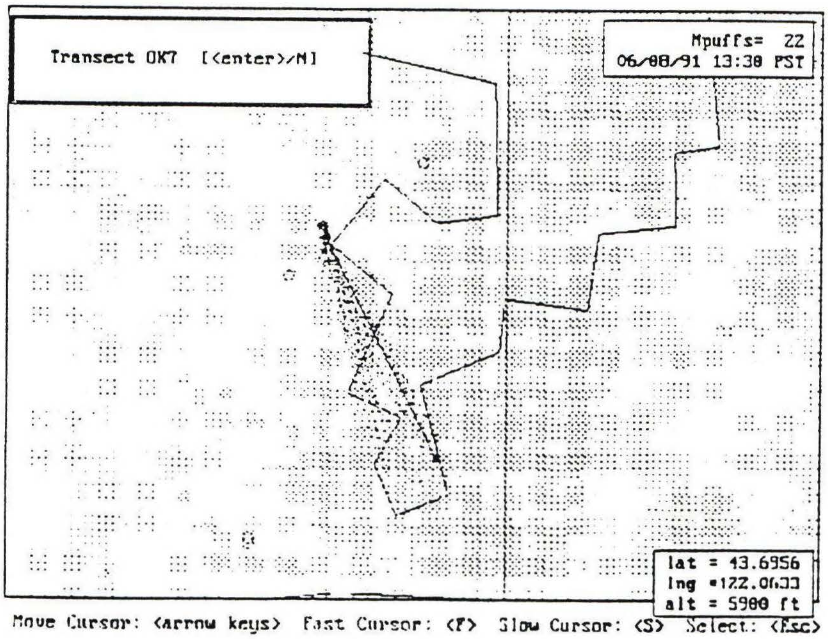
Observed Plume Data
Azimuth: 120
Range: 9,121 meters
Height: 2,342 meters (7,684')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 2.5 thousand meters.

LS1



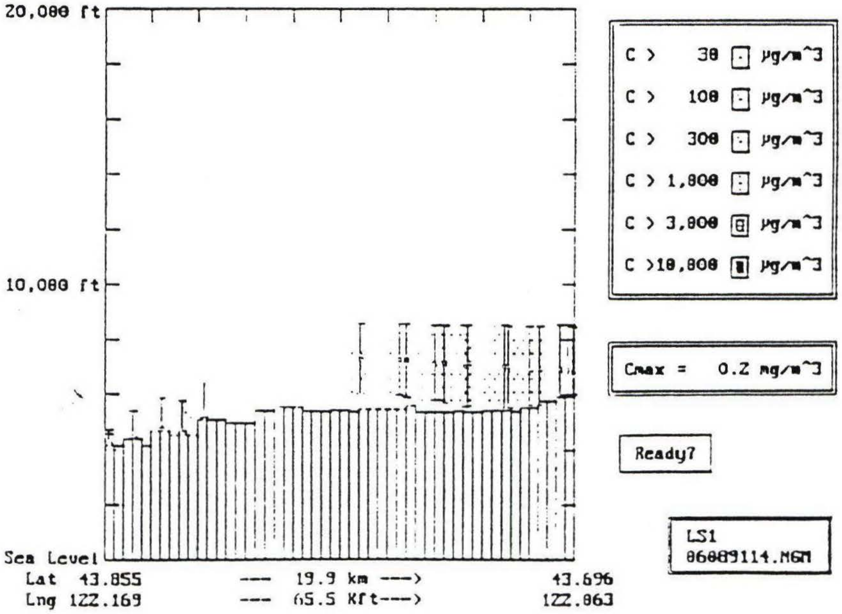


Transect OK? [<enter>/N]

Mpuffs= 22
06/08/91 13:30 PST

lat = 43.6956
lng = 122.0633
alt = 5900 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



20,000 ft
10,000 ft
Sea Level
Lat 43.855 --- 19.9 km ---> 43.696
Lng 122.169 --- 65.5 Kft---> 122.063
C > 30 ⊡ µg/m^3
C > 100 ⊡ µg/m^3
C > 300 ⊡ µg/m^3
C > 1,000 ⊡ µg/m^3
C > 3,000 ▨ µg/m^3
C >10,000 ■ µg/m^3

Cmax = 0.2 mg/m^3

Ready?

LS1
06089114.MGM

JJ3

Unit Information

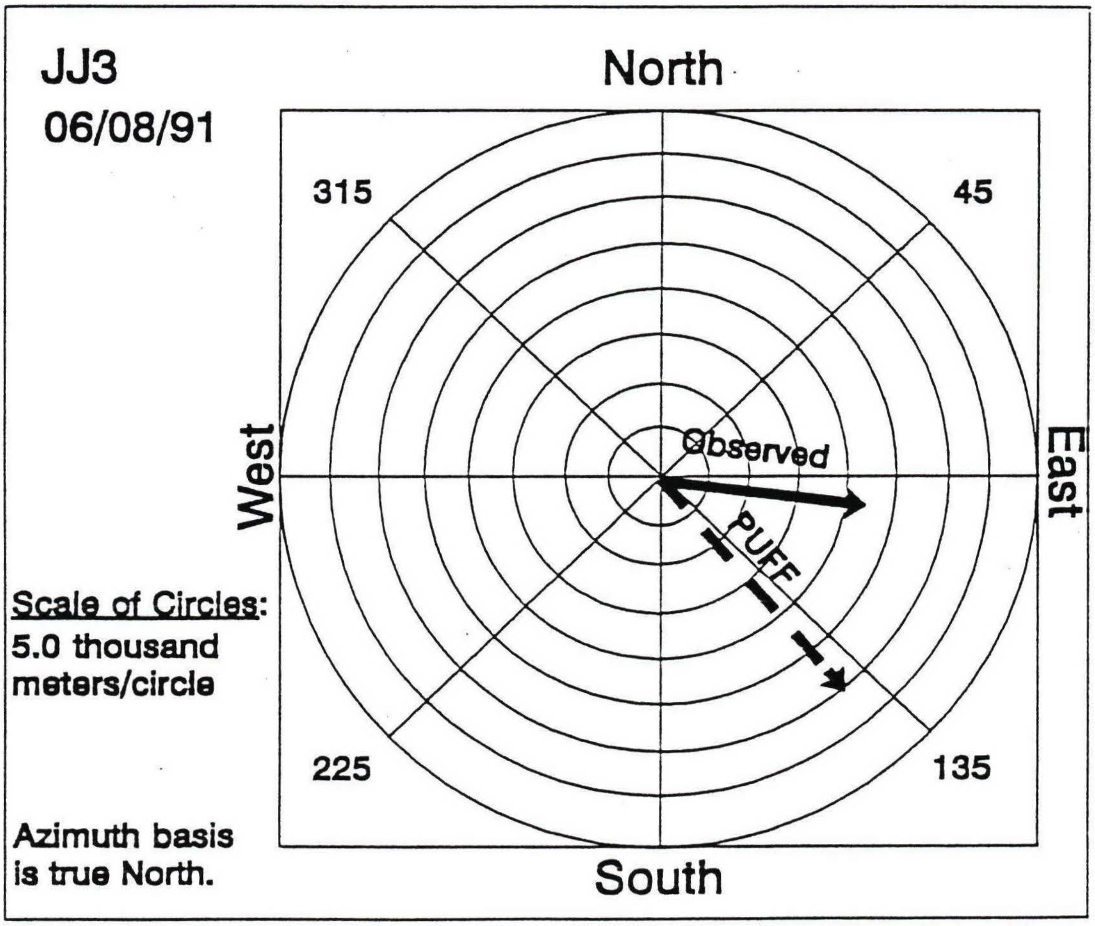
Nat'l. Forest: Willamette
Burn Date: 06/08/91
Elevation: 4,200' msl
Acres Burned: 24
Total Loading: 104.5 t/a
1000hr Moisture: 43%

Weather Information

Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

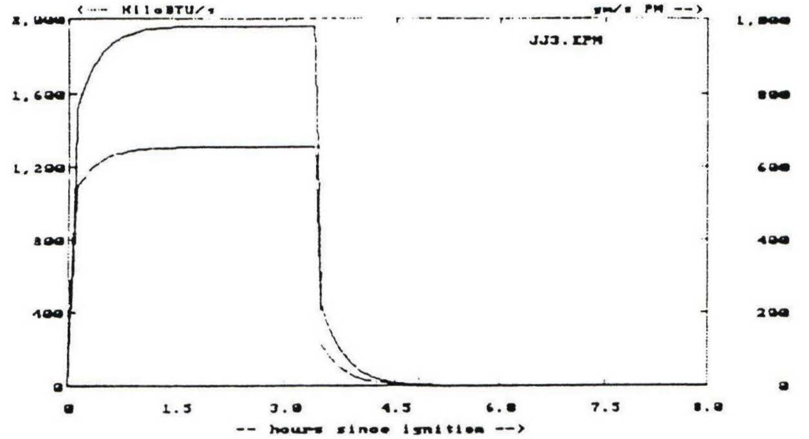
Surface ----
Windspeed: 3 mph

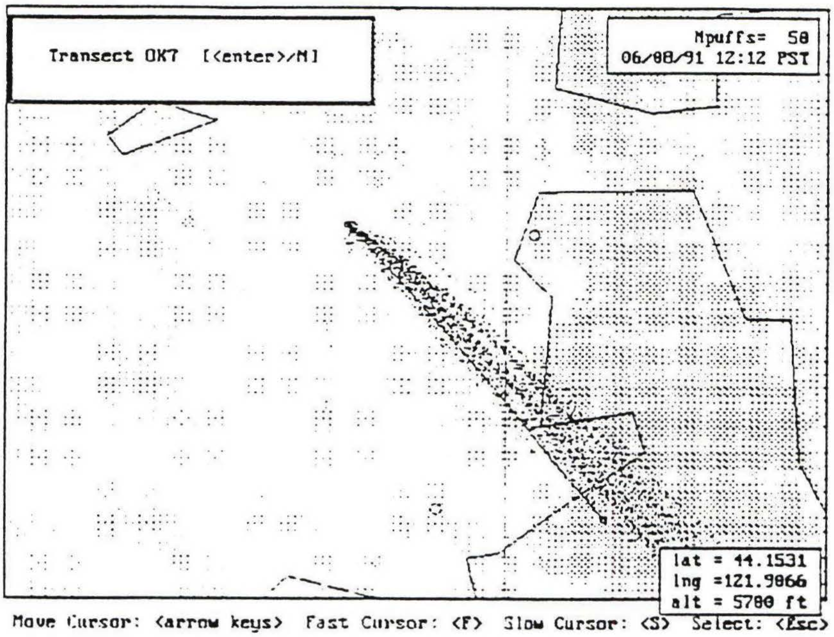
Observed Plume Data
Azimuth: 97
Range: 21,675 meters
Height: 2,011 meters (6,598')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 5.0 thousand meters.

JJ3

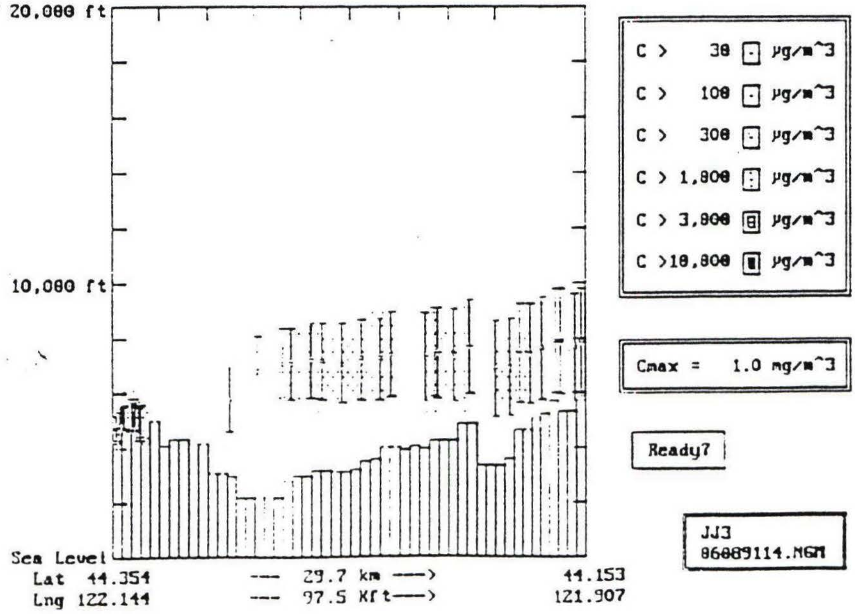



Transect OK7 [<enter>/M]

Npuffs= 50
06/08/91 12:12 PST

lat = 44.1531
lng =121.9866
alt = 5700 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



C > 30 ⊡ µg/m^3
C > 100 ⊡ µg/m^3
C > 300 ⊡ µg/m^3
C > 1,000 ⊡ µg/m^3
C > 3,000 ▣ µg/m^3
C >10,000 ■ µg/m^3

Cmax = 1.0 mg/m^3

Ready?

JJ3
06089114.NGM

- - Assessment - -

TRP3

Unit Information

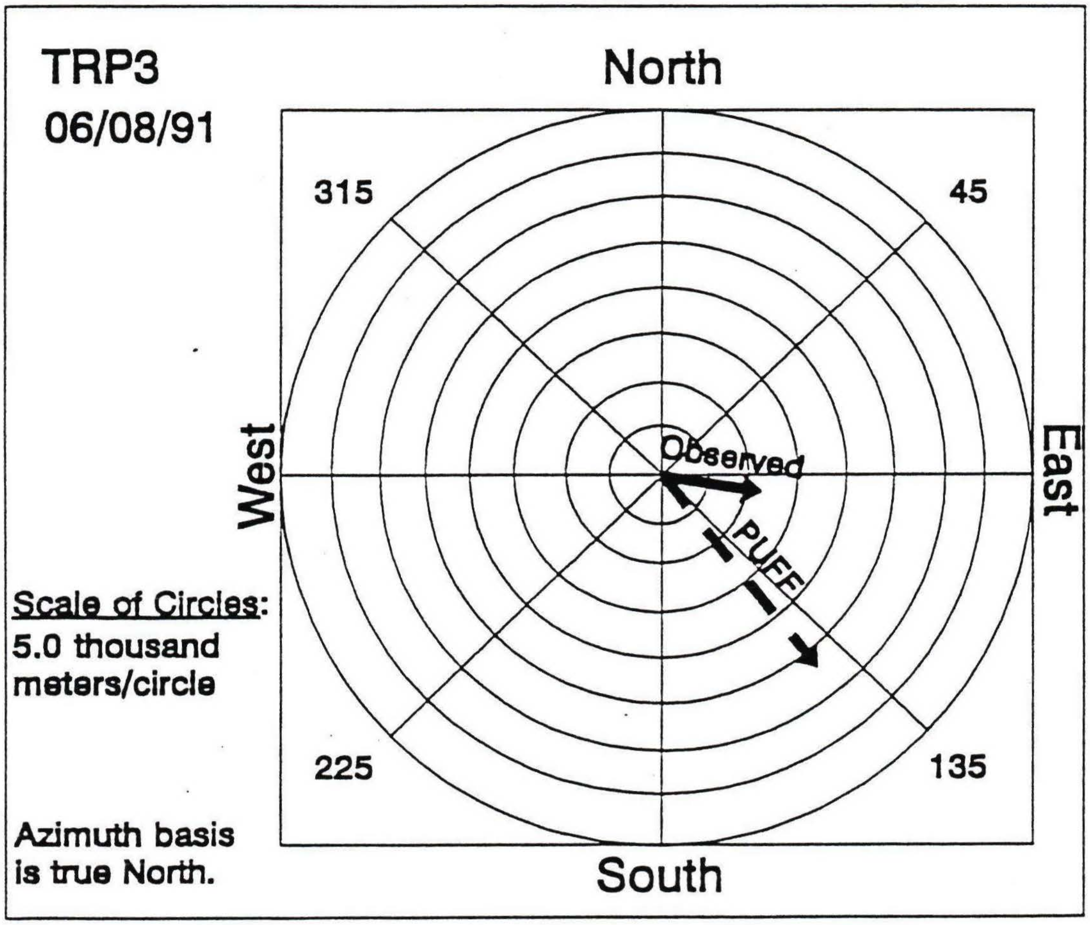
Nat'l. Forest: Willamette
Burn Date: 06/08/91
Elevation: 4,700' msl
Acres Burned: 22
Total Loading: 118.1 t/a
1000hr Moisture: 43%

Weather Information

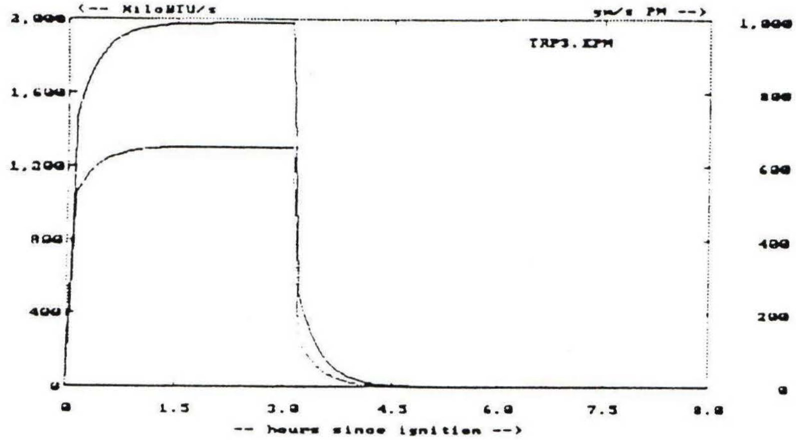
Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

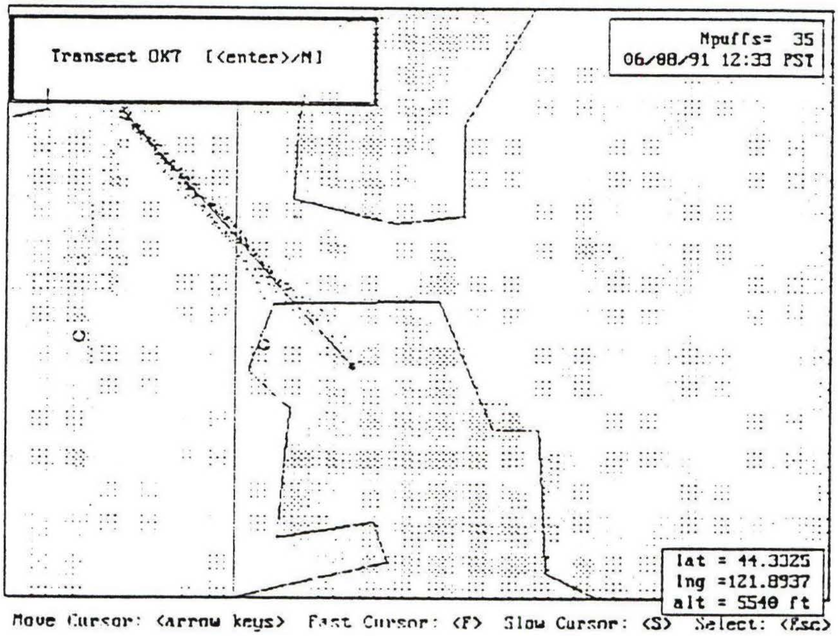
Surface ----
Windspeed: 4 mph

Observed Plume Data
Azimuth: 99
Range: 11,221 meters
Height: 2,011 meters (6,598')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 5.0 thousand meters.



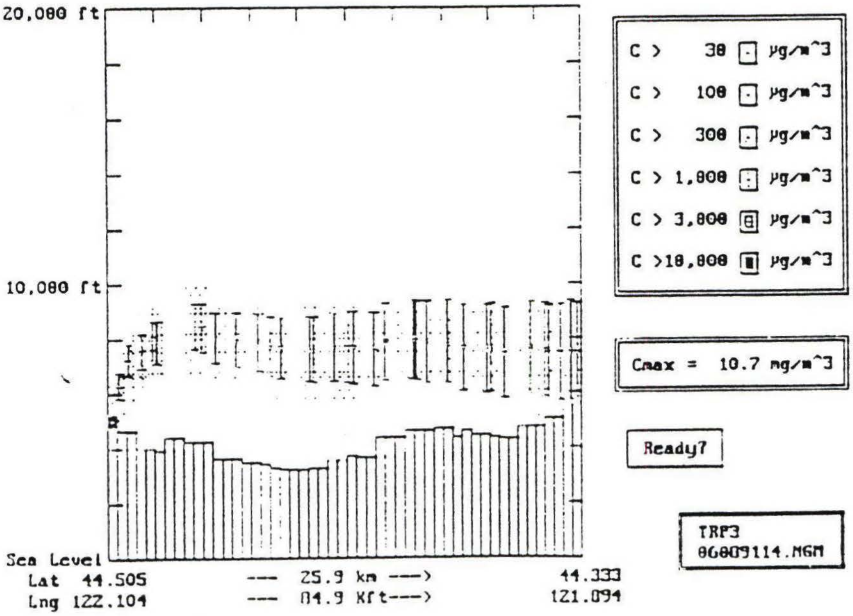


Transect OK? [<enter>/N]

Npuffs= 35
06/08/91 12:33 PST

lat = 44.3325
lng =121.8937
alt = 5540 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



C > 30 ⬚ µg/m^3
C > 100 ⬚ µg/m^3
C > 300 ⬚ µg/m^3
C > 1,000 ⬚ µg/m^3
C > 3,000 ▨ µg/m^3
C >10,000 ■ µg/m^3

Cmax = 10.7 mg/m^3

Ready?

TRP3
06089114.MGM

NH2

Unit Information

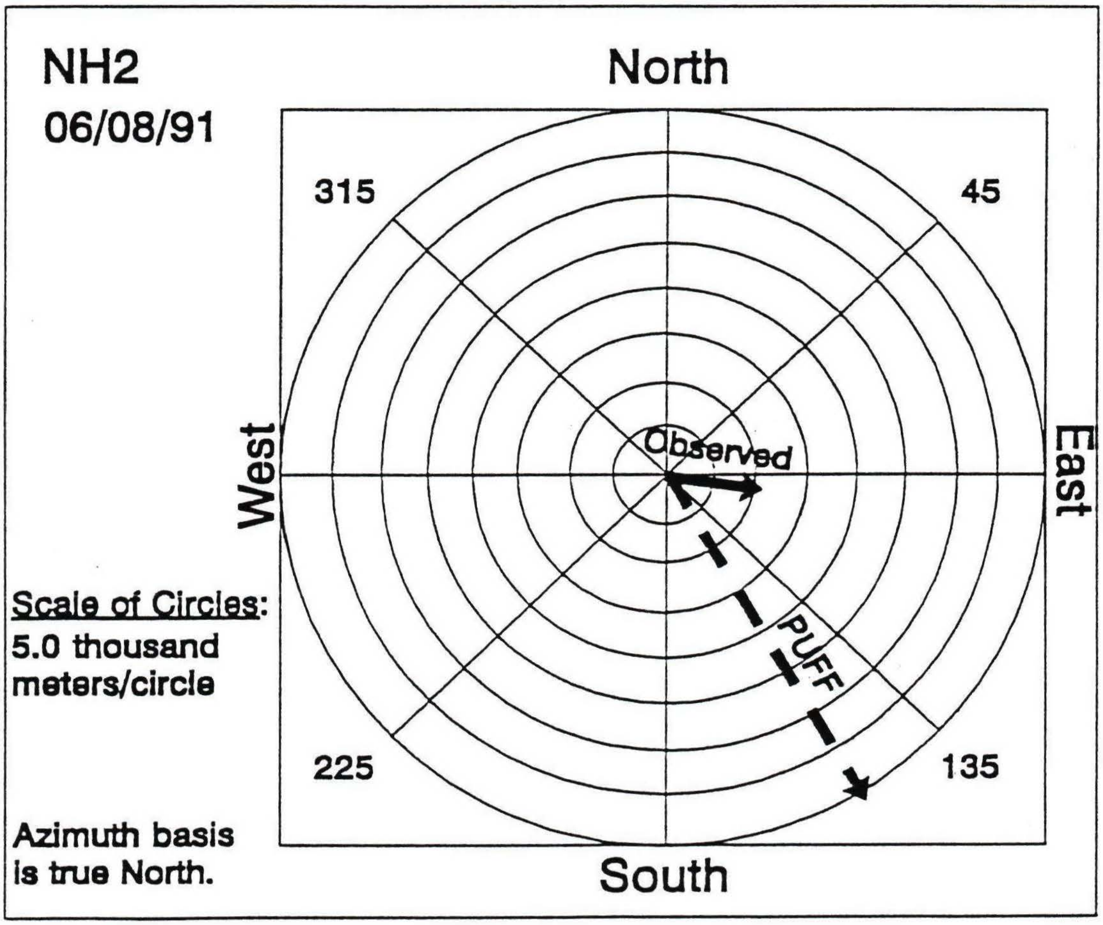
Nat'l. Forest: Willamette
Burn Date: 06/08/91
Elevation: 2,000' msl
Acres Burned: 31
Total Loading: 75.1 t/a
1000hr Moisture: 40%

Weather Information

Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

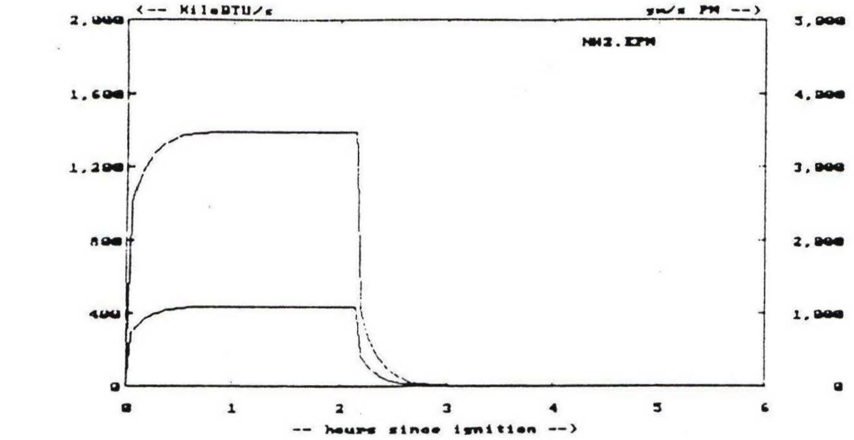
Surface ----
Windspeed: 4 mph

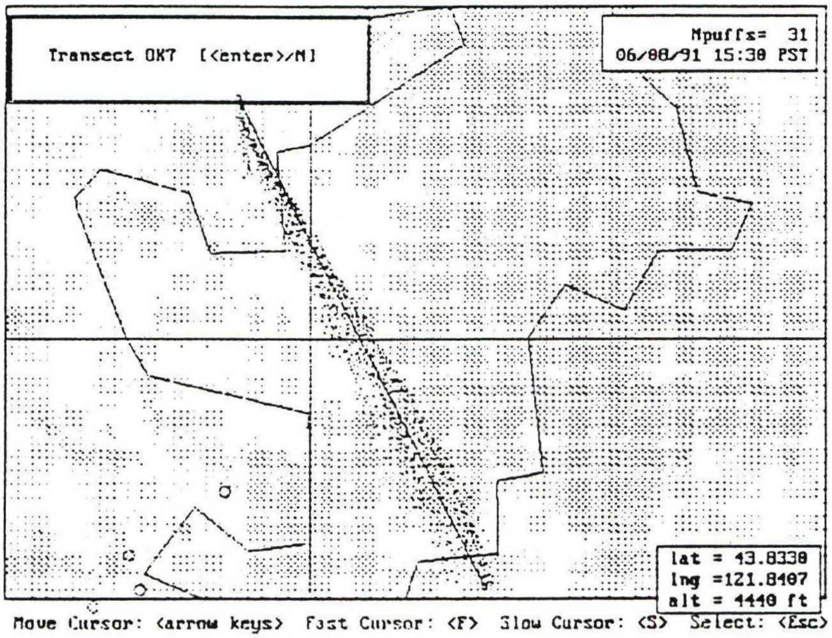
Observed Plume Data
Azimuth: 98
Range: 10,984 meters
Height: 2,560 meters (8,399')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 5.0 thousand meters.

NH2



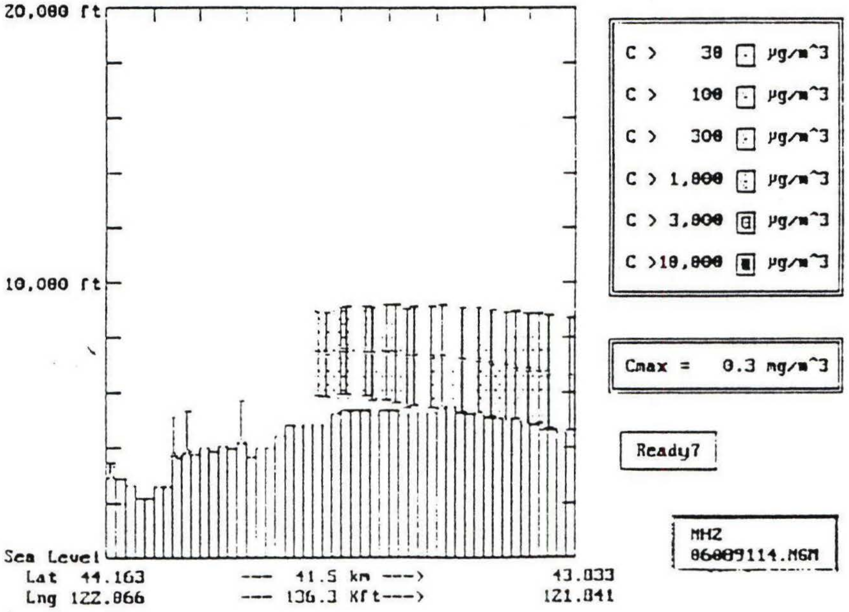


Transect 0K7 [<enter>/N]

Npuffs= 31
06/08/91 15:30 PST

lat = 43.8330
lng =121.8407
alt = 4440 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



C > 30 ⊡ μg/m^3
C > 100 ⊡ μg/m^3
C > 300 ⊡ μg/m^3
C > 1,000 ⊡ μg/m^3
C > 3,000 ▣ μg/m^3
C >10,000 ■ μg/m^3

Cmax = 0.3 mg/m^3

Ready?

NH2
06089114.NGM

SKO21

Unit Information

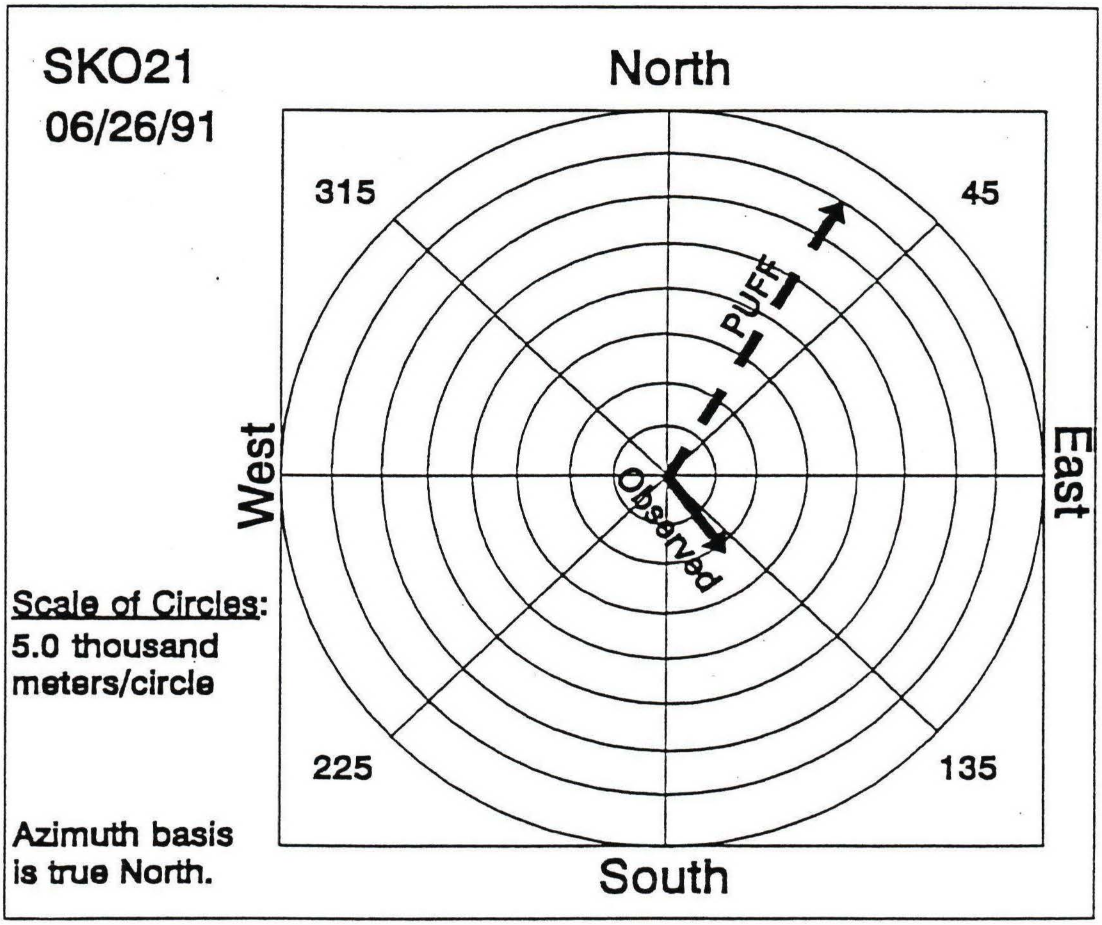
Nat'l. Forest: Willamette
Burn Date: 06/26/91
Elevation: 2,940' msl
Acres Burned: 26
Total Loading: 120.6 t/a
1000hr Moisture: 38%

Weather Information

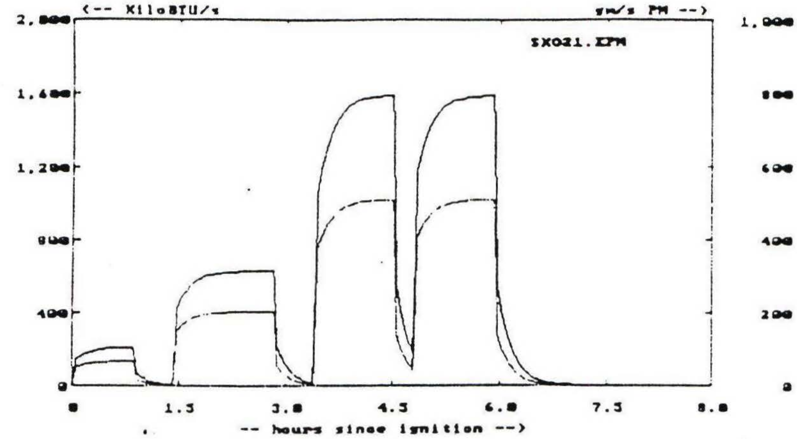
Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

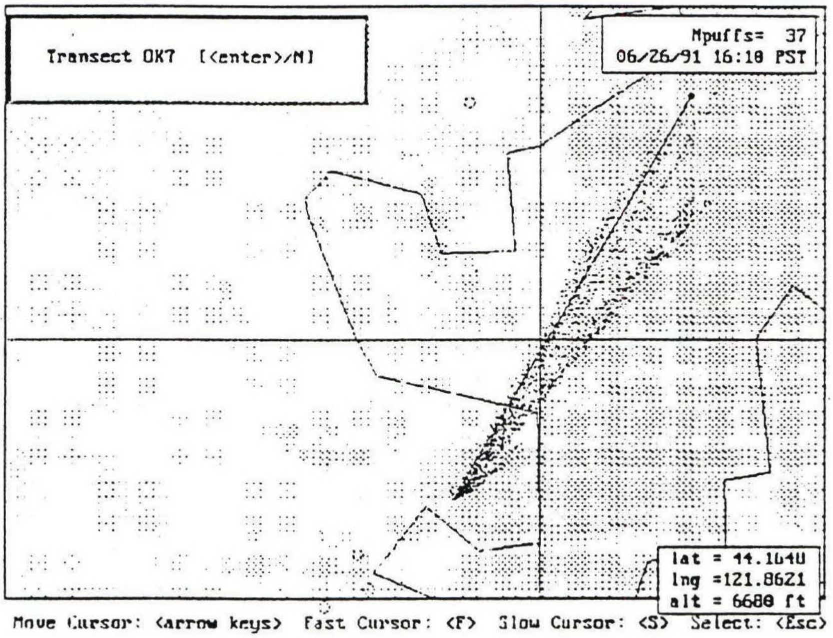
Surface ----
Windspeed: 3 mph

Observed Plume Data
Azimuth: 143
Range: 11,435 meters
Height: 2,289 meters (7,510')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 5.0 thousand meters.

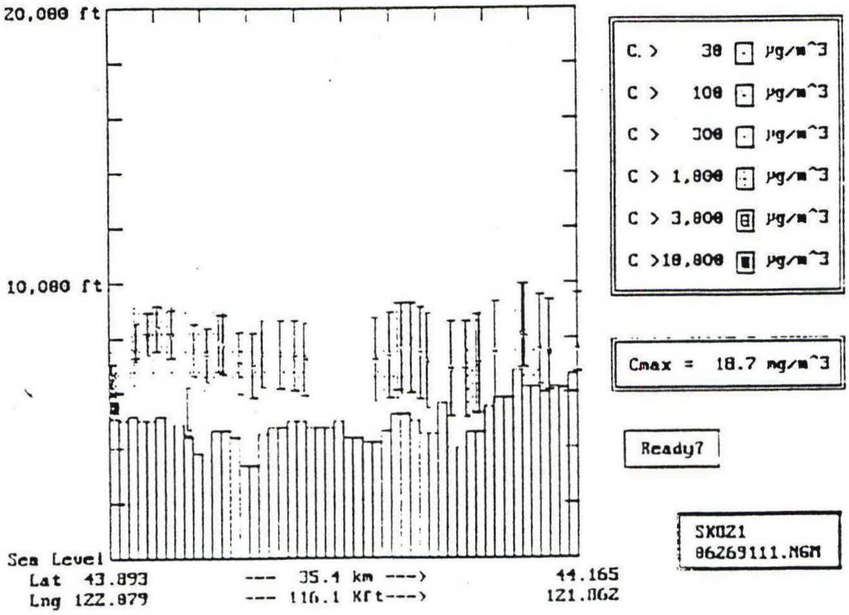



Transect OK7 [<enter>/M]

Npuffs= 37
06/26/91 16:10 PST

lat = 44.1640
lng =121.8621
alt = 6680 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>


20,000 ft
10,000 ft
Sea Level
Lat 43.893
Lng 122.879
--- 35.4 km --->
--- 116.1 Kft--->
44.165
121.062

C > 30 ☐ µg/m^3
C > 100 ☐ µg/m^3
C > 300 ☐ µg/m^3
C > 1,000 ☐ µg/m^3
C > 3,000 ▨ µg/m^3
C >10,000 ■ µg/m^3

Cmax = 18.7 mg/m^3

Ready?

SK021
86269111.NGM

SUN2

Unit Information

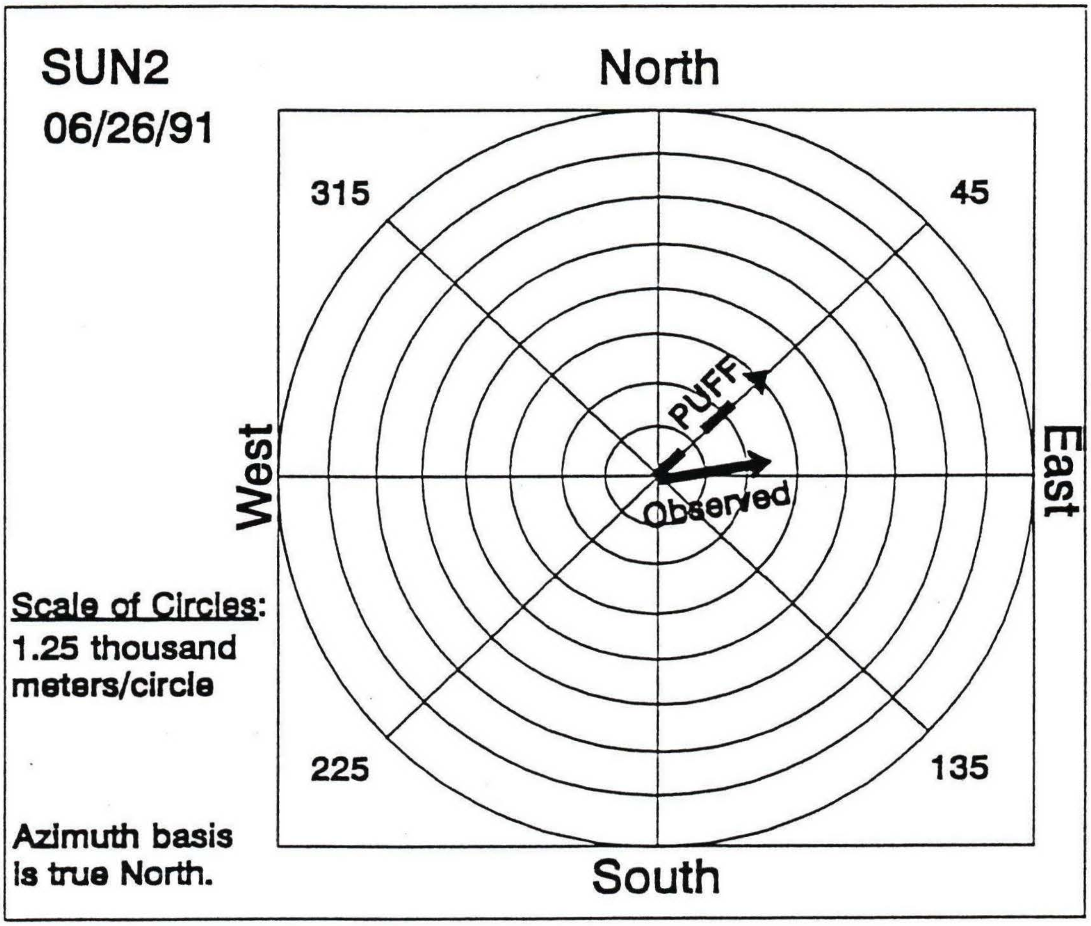
Nat'l. Forest: Willamette
Burn Date: 06/26/91
Elevation: 3,640' msl
Acres Burned: 8
Total Loading: 68.1 t/a
1000hr Moisture: 35%

Weather Information

Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

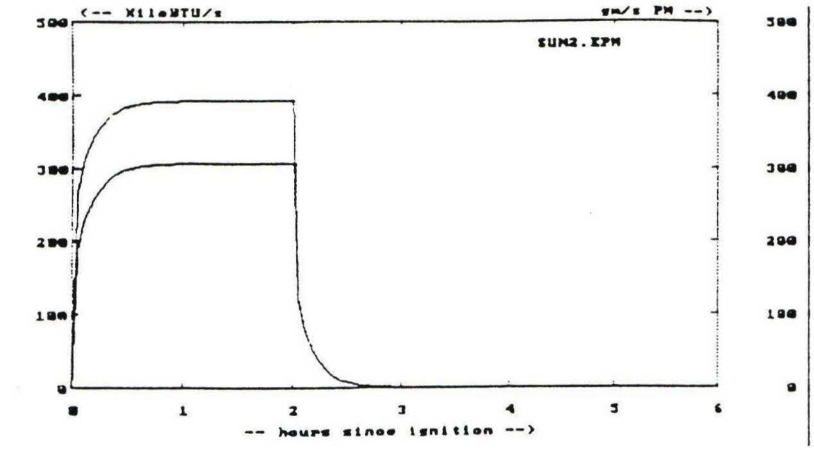
Surface ----
Windspeed: 2 mph

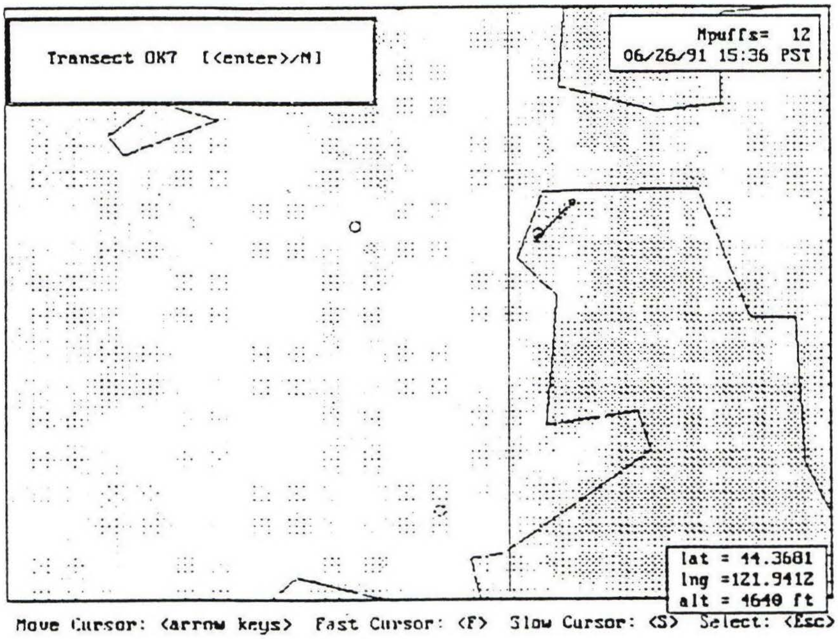
Observed Plume Data
Azimuth: 80
Range: 2,917 meters
Height: 2,344 meters (7,691')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 1.25 thousand meters.

SUN2

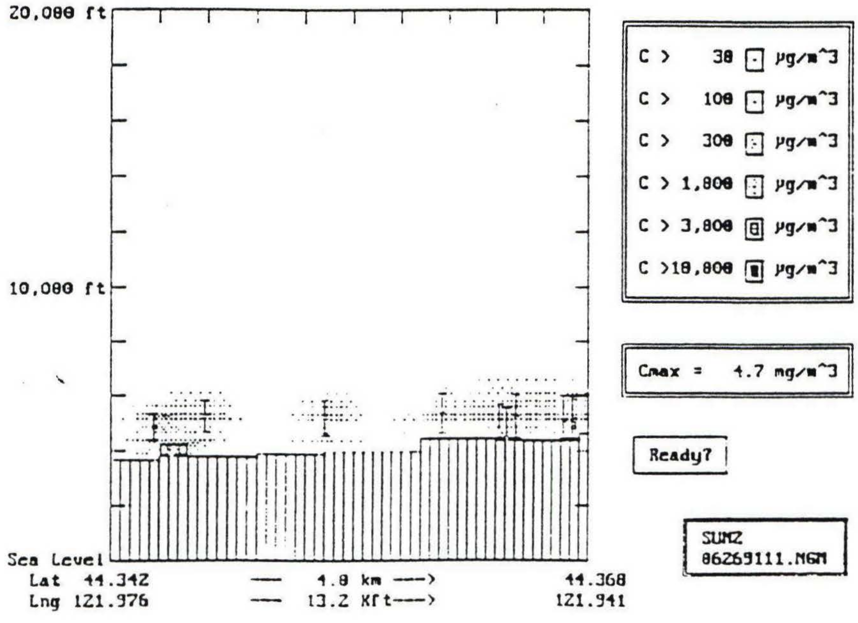



Transect OK7 [<enter>/M]

Mpuffs= 12
06/26/91 15:36 PST

lat = 44.3681
lng =121.9412
alt = 4640 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



20,000 ft
10,000 ft
Sea Level

Lat 44.342 — 4.0 km ---> 44.368
Lng 121.976 — 13.2 Kft---> 121.941

C > 30 ⊡ µg/m^3
C > 100 ⊡ µg/m^3
C > 300 ⊡ µg/m^3
C > 1,000 ⊡ µg/m^3
C > 3,000 ▨ µg/m^3
C >10,000 ■ µg/m^3

Cmax = 4.7 mg/m^3

Ready?

SUN2
06269111.NGM

Unit Information

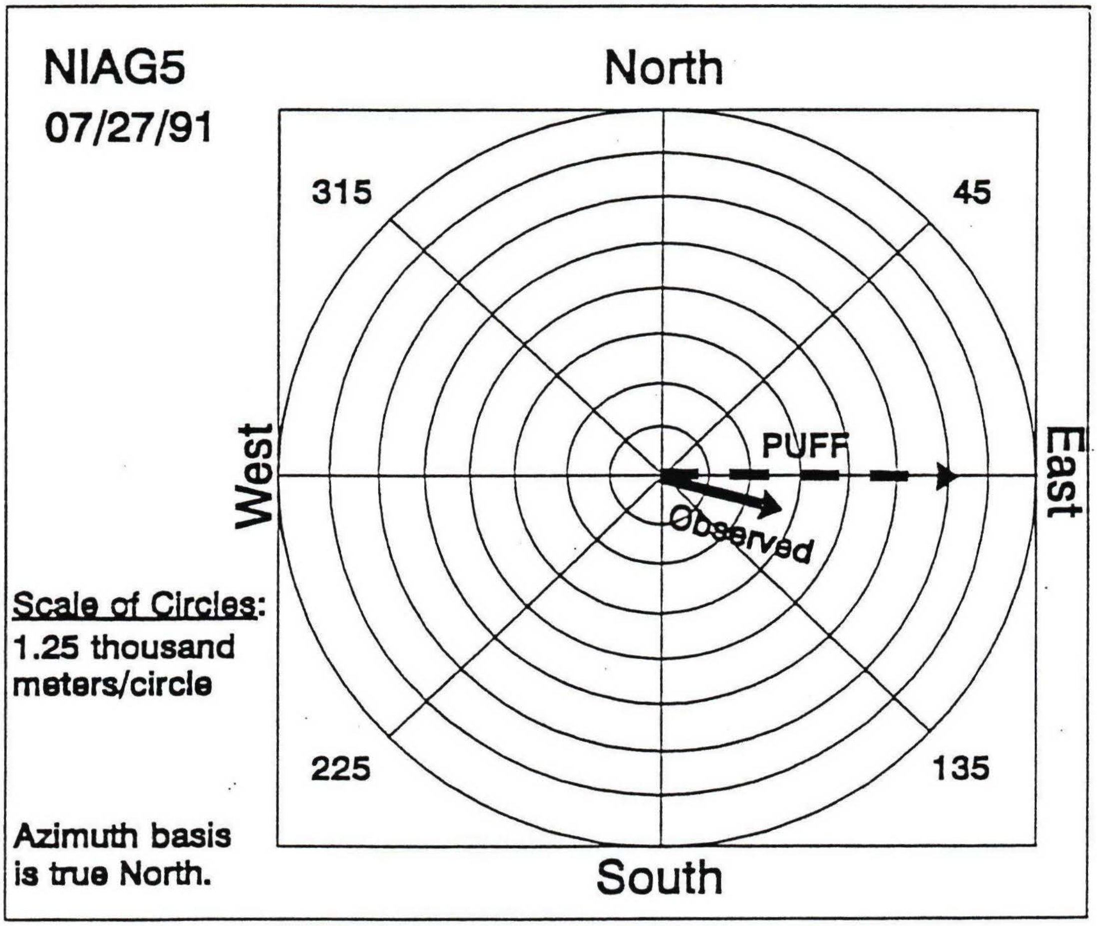
Nat'l. Forest: Siuslaw
Burn Date: 07/27/91
Elevation: 1,600' msl
Acres Burned: 43
Total Loading: 71.5 t/a
1000hr Moisture: 21%

Weather Information

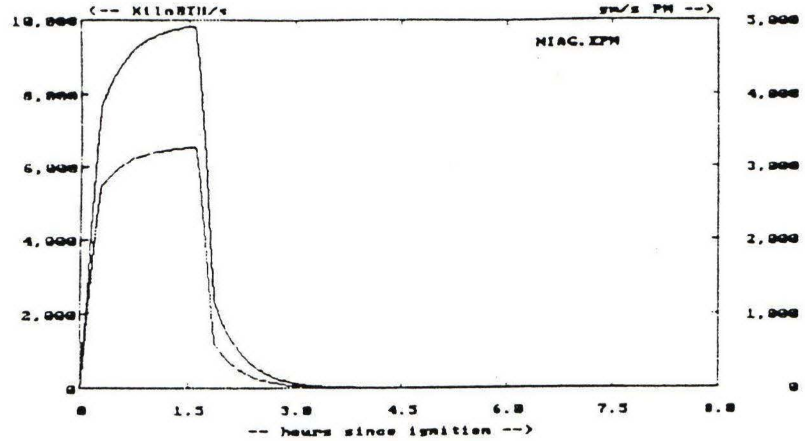
Upper Air --
Stability: Stable
Windspeed: Moderate
Wind Direction: from west

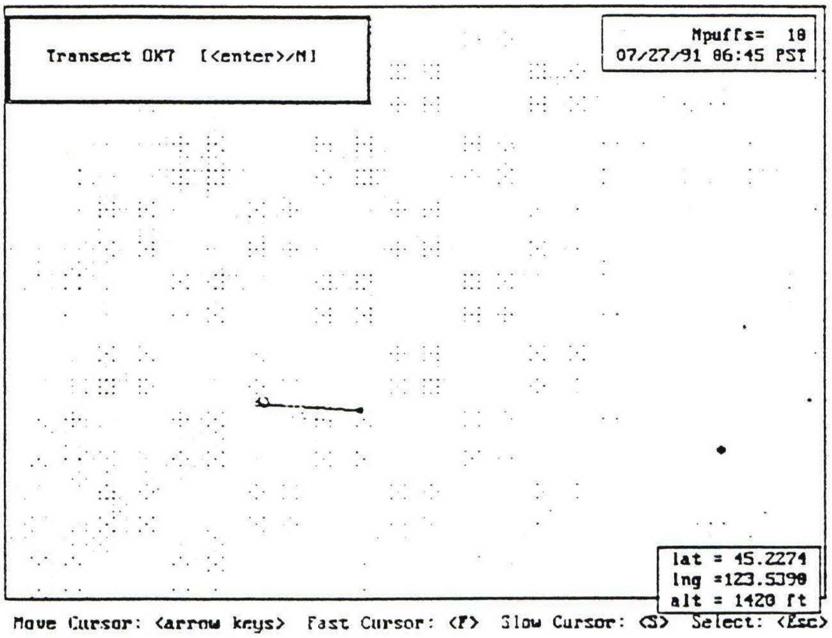
Surface ----
Windspeed: 4 mph

Observed Plume Data
Azimuth: 105
Range: 2,963 meters
Height: 1,310 meters (4,298')



The PUFF-modeled trajectory and range (dashed line) can be compared with airborne GPS observations (solid line). Note the scale of concentric circles, where each circle increments the range by 1.25 thousand meters.



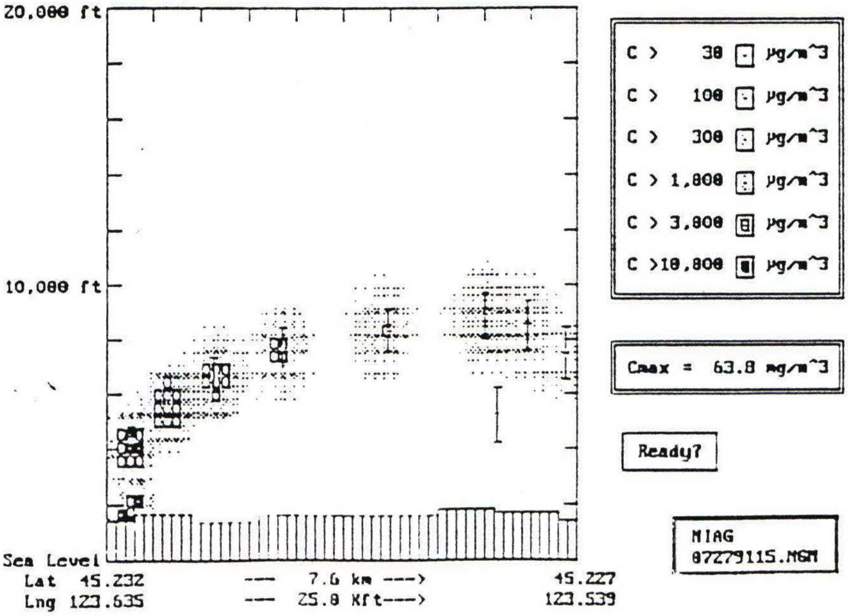


Transect OK? [<enter>/N]

Npuffs= 10
07/27/91 06:45 PST

lat = 45.2274
lng =123.5398
alt = 1420 ft

Move Cursor: <arrow keys> Fast Cursor: <F> Slow Cursor: <S> Select: <Esc>



VIII. Appendices

- A. A Mass-Conserving Algorithm for Interpolating Low-Level Winds
- B. Plume Rise from Prescribed Fires: Model and Data
- C. An Algorithm for Gaussian Puffs

APPENDIX A:

A Mass-Conserving Algorithm for Interpolating Low-Level Winds

H. Harrison
January, 1993

Introduction

PUFF must estimate the near-surface winds at remote sites in complex terrain. Data presently available to this task include:

1. Upper-level soundings at 00Z [4:00 AM PST] at Quillayute, Spokane, Medford, Salem, Boise, and Winnemucca;

2. Coarse-grid [2.5 degLng x 1.25 degLat] weather-service forecasts for the 800mb and 750mb geopotentials and winds at six hour intervals [4 AM 10 AM 4PM 10PM, PST] extending forward over 48 hours.

3. Topographic elevations at 20 ft contours with horizontal grid resolution of 30", roughly 0.9 x 0.6 km at 45 degLat.

Mountain/valley winds are generally driven by local pressure gradients that result from near-surface radiative heating and cooling. If, for example, a valley floor and the south face of a valley wall are both sun-heated to about the same temperature, the *potential* temperatures, θ, will be quite different, owing to the different elevations, and a pressure gradient roughly proportional to $\delta\theta$ will try to move air up the valley wall. To conserve mass, this air must be replaced by inflow along the valley axis, and to conserve momentum the flows will generally follow that axis, rather than turning toward the heated valley wall. At nighttime this process reverses, and in the early morning hours radiation cooling in the valley floor may produce strong thermal inversions.

Note that the *physics* of these winds are predominantly *local*, over vertical scales of a few hundred meters and horizontal scales of a few kilometers, but that [except for the topography] the data available to PUFF represent distant measurements and spatial averaging over many tens of kilometers. Thus we have a serious mismatch between the scales of the governing physics and those of the the data.

What to do?

In previous versions of PUFF I have attempted to extrapolate the upper-level winds towards the surface, with an equilibrium balance among the horizontal forces and a linear perturbation for the effects of the terrain. No explicit constraint was imposed to conserve mass, and near-surface divergence terms were assumed to be balanced by unconstained gradients in the vertical winds, dW/dZ.

Often, however, this algorithm gives unphysical results, for two reasons. Firstly, as I have described in the previous paragraphs, in complex terrain the upper-level winds often [usually!] decouple from the surface winds, and thus are a poor "basis set". Secondly, treating the terrain as a potential perturbation affecting the two-dimensional horizontal flow, without constraining the dW/dZ component of the convergence, can produce erratic and unphysically large vertical winds near the surface, which, to conserve mass, have to be associated with still larger and less physical gradients in dW/dZ.

In partial response to these difficulties, and in preparation for what I anticipate will be a later assignment to interpolate real, local surface data into PUFF's wind-field estimates, the present version [1.14] estimates the surface winds with emphasis on conserving mass at the surface through an explicit function for dW/dZ, as described in the following paragraphs.

A Regression Approach to Interpolation of Near-Surface Wind Fields.

In a very readable papers, Sherman [1978] and Bernard *et al* [1987], describe a method of interpolating initial wind-field estimates with constraints to conserve mass. The procedure devolves into a solution of a three-dimensional Poisson equation with boundary conditions that permit lateral flows, but set the vertical winds equal to zero at the surface. The resulting wind fields are sensitive to a "stability parameter" that affects the relative weight given to conserving mass through the horizontal and vertical components of the winds. With reasonable assumptions for this parameter Bernard *et al* have shown moderately good agreement between model and observations.

The computational overhead of this method, however, appears excessive for PUFF, and some simplification is required.

Responding to this demand I have modified the approach in three ways:

1. Winds are computed only near the surface, where the vertical component is required to be zero normal to terrain-following coordinates, and:

$$W = U\ H_x + V\ H_y \qquad [1]$$

In [1]:

W = the upward scalar component of the near-surface vector wind, in Cartesian coordinates.

U = the eastward-flowing scalar component of that wind.

V = the northward-flowing component.

H = the local terrain altitude, above sea level.

$H_x = dH/dX$, the eastward gradient of the terrain.

$H_y = dH/dY$, the northward gradient.

2. Near the surface, the vertical gradient of W is assumed to be:

$$W_z = dW/dZ = - W\ /\ Z_o \qquad [2]$$

where Z_o is a constant, characteristic length over which W_z decays towards zero.

3. A variance, G, is defined as

$$G = \sum\left[(U_1-U_o)^2+(V_1-V_o)^2 + \phi\ (U_x+V_y+W_z)^2\right] \qquad [3]$$

and a minimum in G is sought with respect to U_1 and V_1, given observations U_o, V_o, and specified ϕ and Z_o.

After some algebra, solutions of [3] may be expressed as:

$$U_1 = [C_{11}\ U_o + C_{12}\ V_o + C_{13}\ \alpha]\ /\ [1 + |C_{13}|] \qquad [4a]$$

$$V_1 = [C_{21}\ U_o + C_{22}\ V_o + C_{23}\ \alpha]\ /\ [1 + |C_{23}|] \qquad [4b]$$

where:

$$C_{11} = [1 + \epsilon H_y^2] / [1 + \epsilon(H_x^2 + H_y^2)] \quad [5a]$$

$$C_{22} = [1 + \epsilon H_x^2] / [1 + \epsilon(H_x^2 + H_y^2)] \quad [5b]$$

$$C_{12} = -\epsilon H_x H_y / [1 + \epsilon(H_x^2 + H_y^2)] \quad [5c]$$

$$C_{21} = C_{12} \quad [5d]$$

$$C_{13} = \epsilon H_x (Z_o/X_o) / [1 + \epsilon(H_x^2 + H_y^2)] \quad [5e]$$

$$C_{23} = \epsilon H_y (Z_o/X_o) / [1 + \epsilon(H_x^2 + H_y^2)] \quad [5f]$$

$$\alpha = [(U_+ - U_-) + (V_+ - V_-)] / 2 \quad [5g]$$

In [5a], and thereafter, X_o is the lateral dimension of the grid cells [1, 2, 4, or 8 km], the "+" subscripts refer to evaluations of U and V at the eastward and northward adjacent grid cells, respectively, and the "-" subscripts to the westward and southward cells.

The dimensionless positive coefficient, $\epsilon = \phi/Z_o^2$, assigns a relative weight to force mass convergence in equation [3], with respect to the weight assigned to preserving the intitial velocity guesses, U_o and V_o. Generally, for stable air, we want this factor to be large [with respect to $H_x^2 + H_y^2$]. When this is so the coefficients in [4a,b] become independent of ϵ and equal to:

$$\begin{aligned}
C_{11} &= [H_y H_y] / [H_x^2 + H_y^2] \\
C_{12} &= -[H_x H_y] / [H_x^2 + H_y^2] \quad = \quad C_{21} \\
C_{21} &= -[H_y H_x] / [H_x^2 + H_y^2] \quad = \quad C_{12} \\
C_{22} &= [H_x H_x] / [H_x^2 + H_y^2]
\end{aligned}$$

$$\begin{aligned}
C_{13} &= H_x [Z_o/X_o] / [H_x^2 + H_y^2] \\
C_{23} &= H_y [Z_o/X_o] / [H_x^2 + H_y^2]
\end{aligned}$$

I have explored the solutions of these equations, in both the small- and large-ϵ approximations, with various Z_o and surface topography. The resulting wind fields appear "sensible", and the problems associated with unreasonable W_z that resulted from the two-dimensional force balance model that I discussed above, are effectively eliminated.

Notice that in the large-ϵ limit, the only adjustable parameter is Z_o. When this is small [<100m] iterative solutions of [4a,b] are fast, "local", and they approximate projections of the $[U_o,V_o]$ onto the topographic contours. When Z_o is large [>1000m] and C_{13} and C_{23} approach or exceed unity, then iterative solutions of [4a,b] converge more slowly [but they *do* converge] and the resulting wind fields are dominated by the lateral boundary conditions imposed on U and V. Tentatively, I have selected ϵ=300 (dimensionless) and Z_o = 100m as standard parameters.

Equations [4] may be considered as a "filter" that processes a first approximation of a wind field $[U_o,V_o]$ into improved estimates $[U_1,V_1]$ that adjust to the terrain with conservation of mass. This begs the issue, however, about how to get started with sensible $[U_o,V_o]$. Failing better *local* temperature data or real observations, PUFF offers two options:

1. The upper level winds can be extrapolated to the surface, [despite all reservations about the dominating effects of local temperature gradients that I discussed above], or

2. Guided by measurements or intuition, users may impose a wind direction and velocity at a single point near the surface [as for example at a valley floor near to a prospective burn site].

With either choice, PUFF applies the conservation filter that I have described here to improve estimates of the near-surface winds by forcing accomodation to the local topography. The filter is well adapted to better data also, when they become available.

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Plume Rise from Prescribed Fires: **Model and Data**

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Abstract

In support of efforts to model the trajectories of smoke from forest biomass, we have undertaken a program to observe the dynamics of smoke plumes from prescribed fires in the Pacific Northwest. These observations have been combined with meteorological data and estimates of the test fires' fuel mix and ignition protocols into a semi-empirical model that usefully predicts plume heights as functions of time.

Introduction

The USDA Forest Service is presently developing an operational model to predict plume trajectories from prescribed burning of forest biomass, for which we require a simple subroutine to predict plume-rise dynamics.

The classic paper on plume rise from large fires is by Morton, Taylor and Turner [MTT, 1959], who wrote and solved a two dimensional equation set conserving mass, momentum, and buoyancy. More recently, Penner, Hasselman, and Edwards [PHH, 1985] demonstrated reasonable results with a three dimensional numerical model that included effects of vorticity and condensation, but their work (on a Cray) is really not portable as a subroutine for operational use by others. Carrier, Fendell, and Friedman [1985], and Manins [1985] separately revised the MTT approach in different ways and applied it to data from several large fires, with moderately good results. Penner *et al.* suggest that this agreement may be fortuitous, owing to the two-dimensional models' neglect both of vorticity and of the horizontal extent of the fires, and to their sensitivity to an assumed entrainment parameter. But the three-dimensional model is itself not immune to this last criticism, nor is the approach that we shall present here.

In this present note we shall describe a semi-empirical plume-rise model that admits simple, closed expressions for the plume dynamics, and we compare the results of this model with preliminary data from flight observations of the smoke from prescribed fires.

The Model

We begin with a force balance on a puff of smoke, for which:

mass · acceleration = buoyancy - entrainment drag
- aerodynamic drag

$$N\ V\ dw/dt = g\ V\ \delta N - w\ N\ dV/dt - 1/2\ C_a\ N\ A\ w^2 \qquad [1]$$

In equation [1] and hereafter:

N = the atmospheric density [kg/m^3].
δN = the density difference between the interior of the puff and the ambient air.
V = the volume of the puff.
T = the temperature of the puff.
δT = the temperature difference between the interior of the puff and the ambient air.
w = the vertical velocity of the puff.
t = time.
g = the gravitational constant [9.8 ms^{-2}].
C_a = a dimensionless aerodynamic drag coefficient.
A = the area of the top face of the puff.

We assume a hocky-puck volume element, as in figure 1, with a height, h, and a circular upper face of diameter, D. As the puck rises, a fraction of the air above it, α, is entrained into the puck, and $1-\alpha$ is diverted around it. The entrained air acquires the plume's upward momentum over a vertical distance, h.

Notice that $\delta N = N\ \delta T/T$,, that $V = A\ h$, that the volume-flux, F_v (m^3s^{-1}), into the top of the puck is $\alpha\ w\ A$, and that

$$(1/V)\ dV/dt = F_v\ /V\ = \alpha w/h\ . \qquad [2]$$

With these substitutions equation [1] becomes:

$$dw/dt = g\ \delta T/T - [(\alpha + 1/2\ C_a)/h]\ w^2 \qquad [3]$$

We have measurements or can guess reasonable values for C_d, α, and h. If we knew $(\delta T/T)_z$, we could integrate [3] directly, and the problem would be solved.

$\delta T/T$

If the puff did *not* mix with the ambient air it would rise along a dry adiabat, as in curve (a) of figure 2, until it intersected the ambient sounding (b) at a point of neutral buoyancy, Z_n. In the real case, with mixing [but without water condensation, in this example] the trajectory resembles (c).

Let us partition $\delta T/T$ into terms that separately represent the diffusive mixing and the altitude dependence of the temperature structure:

$$(\delta T/T)_z = (\delta T/T)_o \cdot (V_o/V_z) \cdot \theta_z \qquad [4]$$

In [4] and after the subscript $()_z$ labels functions of altitude, and $()_o$ identifies values at the surface. The second factor on the right accounts for dilution as the puff rises and mixes, and the third is the relative temperature difference between an unmixed puff and the ambient air, normalized by its value at the surface.

From curves (b) and (c) of figure 2,

$$\theta_z \approx 1 - z/Z_n \qquad [5]$$

A more exact expression than [5] can be derived from measured soundings when that is appropriate.

The mixing factor in [4] can be rewritten as:

$$(V_o/V_z) = [1 + \delta V/V_o]^{-1} = \left[1 + \int (1/V_o)(dV/dt)\, dt \right]^{-1}$$

which, with the righthand side of equation [2], becomes:

$$(V_o/V_z) = \left[1 + \alpha/h \int w\, dt \right]^{-1} = [1 + \alpha z/h]^{-1} = [1 + z/H_z]^{-1} \qquad [6]$$

In [6] H_z is h/α. There now remains the task of measuring or modeling $(\delta T/T)_o$, the fractional temperature increment at the surface that derives from the fire, and Z_n, the plume's maximum altitude.

$(\delta T/T)_o$: Slash-Fire Temperatures near the Surface

The parameter $(\delta T/T)_o$ in equation [4] is an average over a volume element at the surface, within which higher flame temperatures are diluted and cooled by air advecting inward along a distribution of complicated trajectories.

By conservation of energy, we can write:

$$(\delta T/T)_o = [(P/A)\ \tau] \;/\; [T_o\, C_p\, N\, h] \qquad [7]$$

In [7] (P/A) is the instantaneous power density, C_p is the specific heat of air at constant pressure, and τ is a characteristic heating time that will vary approximately with $A^{1/2}$, and inversely with a velocity that in turn should scale with $(P/A)^{1/2}$.

Substituting and rearranging, equation [7] may be rewritten as:

$$(\delta T/T_o)_o = \beta\ (P/P_o)^{1/2} \qquad [8]$$

In [8] P is the intantaneous power of the burn, P_o is a standard power [say, one GigaWatt] and β is a dimensionless coefficient that incorporates h, C_p, N, and T_o.

Z_m: The Maximum Plume Rise

If the simple picture of figure 2 holds approximately, then the maximum plume rise, Z_m, may be estimated from the temperature rise at the surface, δT_o, and the dry and ambient lapse rates, Γ_d and Γ_a:

$$Z_m \approx \delta T_o/[\Gamma_d - \Gamma_a]$$

$$Z_m \approx H_o\ (P/P_o)^{1/2} \qquad [9]$$

Higher approximations than [9] can (and should) be used, when local sounding data are available.

Putting it together

The model is now at least functionally complete. Substituting [5], [6], [8], and [9] into [3] gives:

$$dw/dt = F(z) - G\,w^2 \qquad [10]$$

where: $F(z) = g\beta\,(P/P_o)^{1/2}\,[1-z/Z_n]/[1+z/H_m]$

$G = [\alpha + 1/2\,C_d]/h$

When w is greater than a few cm/s then equation [10] can to a good approximation be solved in the steady-state. That is:

when $|dw/dt| \leq |F| \approx |G\,w^2|$,

then $w(z) \approx [F/G]^{1/2}$.

Finally, putting this all together gives:

$$w(z) = W_o\,(P/P_o)^{1/4}\left[[1-z/Z_n]/[1+z/H_m]\right]^{1/2} \qquad [11]$$

$$Z_n \approx H_o\,(P/P_o)^{1/2} \qquad [12]$$

$$z = \int w\,dt \qquad [13]$$

Equations [11]-[13] comprise the simple model of this study.

In [11]: $w(z)$ is the instantaneous vertical velocity of a puff;

P is the instantaneous power at the time of the puff's formation;

In [12]: Z_n is the asymptotic height above the surface at which the puff achieves neutral buoyancy; and

In [13]: z is the current puff height.

W_o, H_o, and H_m are empirical coefficients to be determined from data.

Users should be cautious with [12], especially with small fires for which the details of the ambient temperature profiles become important [as with near-surface inversions], and with very large fires where [12] can spuriously estimate Z_n values that are above the tropopause. More exact estimates of Z_n and higher approximations to equation [11] can be derived from local soundings, when that is appropriate.

Data

To provide a data base from which to evaluate plume-rise models the US Forest Service has undertaken a series of more than 20 flights to observe the dynamics of smoke from prescribed fires of forest slash in the Pacific Northwest [Hardy and Doughty, 1992].

A protocol of this study has been to use one subset of these data to evaluate empirical parameters, and another to score the results. For the first subset we have chosen 5 fires that effectively span the range of typical peak power emissions. For each of these fires we estimated the power-release profiles by an algorithm that accounts for fuel characteristics such as amount, species, and moisture content, the weather, and ignition patterns and rates [Sandberg and Peterson, 1984]. Note that these are not free fires, but that the burn rates are controlled by ignition crews. For two of the 5 calibration fires [UPC8 and TR4] distinct double maxima permitted separate estimates of the peak heights achieved by puffs associated with the peak emissions, figure 3 and Table I.

Table I

Label	Date Mo/Da/Yr	Peak Pwr GigaWatts	Plume Rise (m) Above Surface
Grant	07/23/91	0.58	700
UPC8(b)	06/06/91	0.81	1445
PG9	06/17/91	1.19	1242
UPC8(a)	06/06/91	2.12	1828
Astro	06/06/91	2.75	2383
TR4(b)	06/03/92	3.14	2608
TR4(a)	06/03/92	6.61	3618

The smallest fire of this set [Grant] was unusual also in the early hour of its ignition [6:30 AM], when a radiation inversion near the ground presented a temperature lapse rate very different from the idealization of equation [9]. To account for this, and to provide a flexibility to adapt the plume-rise equation to local sounding information, when it is available, equation [12] may be modified to:

$$Z_n = H_o \ (P/P_o)^{1/2} - H_i \qquad [12b]$$

where H_i is an inversion height that may be parameterized from the sounding, or empirically from the season, cloud cover, and time of day. In this form, the data of Table I are well approximated by:

$$Z_n(\mathrm{km}) = 1.54 \ [P(\mathrm{GigaWatts})]^{1/2} - 0.276 \qquad [12c]$$

Airplane scheduling logistics and the obscuring of later puffs by the trailing smoke from earlier ones makes more difficult the resolution of the vertical velocities of buoyant plumes. With somewhat less precision than for the determination of the maximum plume heights, a non-linear regression of data from the relatively well-observed leading puff from TR4(b) gave:

$$W_o \approx 3.2 \ \mathrm{ms}^{-1}$$ [14a

and $$H_m \approx 500 \ \mathrm{m}$$ [14b

with uncertainties that may exceed 50%.

Figures 4 and 5 compare observations with the maximum plume rises, Z_m, computed from their estimated peak power releases, as in figure 3, and equations [11]-[13] with the numerical parameters from [12c] and [14a,b]. Figure 5 illustrates the temporal evolution of the plume-rise equations, parameterized by power levels.

Discussion and Summary

In equations [11] through [14] we have presented a simple and useful algorithm to estimate the plume dynamics of smoke from prescribed forest slash fires that display instantaneous power releases in the range of 0.1 - 10 GigaWatts. Guided by a force-balance equation, [1], and dimensional arguments affecting the temperature rise near the surface, [7] and [8], we suggest that the maximum plume heights should vary approximately with the square root of the power, [8], and that the initial vertical velocity should vary with $P^{1/4}$, [11].

That the maximum plume rise varies approximately as $P^{1/2}$ appears to be well confirmed by our observations [figure 4]. This may perhaps seem a controversial finding; however, Manins has argued from theory and data that maximum plume heights of very large fires [up to 10^4 GW] may vary approximately as $P^{1/4}$ [Manins, 1985]. We believe that this discrepancy is more apparent than real, and that it derives from the very different temperature profiles in the stratosphere, into which the plumes from fires larger than about 10 GW will attempt to penetrate. This disagreement should serve as a warning to casual users of our [or Manins'] formulae, not to extrapolate out of the bounds of confirming measurements.

At the other end of the scale, for 'small' fires [$P < 0.1$ GW], the details of the near-surface temperature soundings tend to overwhelm the approximation of equation [9], and either (preferably) real temperature profiles should be measured, or (less satisfactorily) various *ad hoc* corrections can be attempted, as in [12c].

It is perhaps worth noting that in equations [7] and [8] the fires' areal extent drops out of the derivation of the succeeding formulae. Penner *et al* [1985] make a point of criticizing this independence of fire-area in the work of Carrier *et al* [1985]. It appears, however, that with prescribed fires of forest slash ... where forest practices result in fuel densities [kg/m^2] that are fairly uniform, and where the combustion rate is controlled by a local burn crew ... the effects of a burn's area are second order.

An important exception to this, however, occurs when separate burn crews [or a "helitorch"] simultaneously ignite quite different sections of a very large burn field. In this case, as occurred in the "Hill Township" fire [McRae and Stocks, 1987], the present formulae should be used (if at all) as if with independent smaller fires.

Finally, it should be noted again that in this study a subset of a larger data base was selected to evaluate the parameters of our model, so that the full data set might then be used more impartially to validate the model's precision.

We're working on it.

Acknowledgement
It's all very well to tap at a computer or fly around in a plane, but the *real* work for this study was done by the crews on the fire line.

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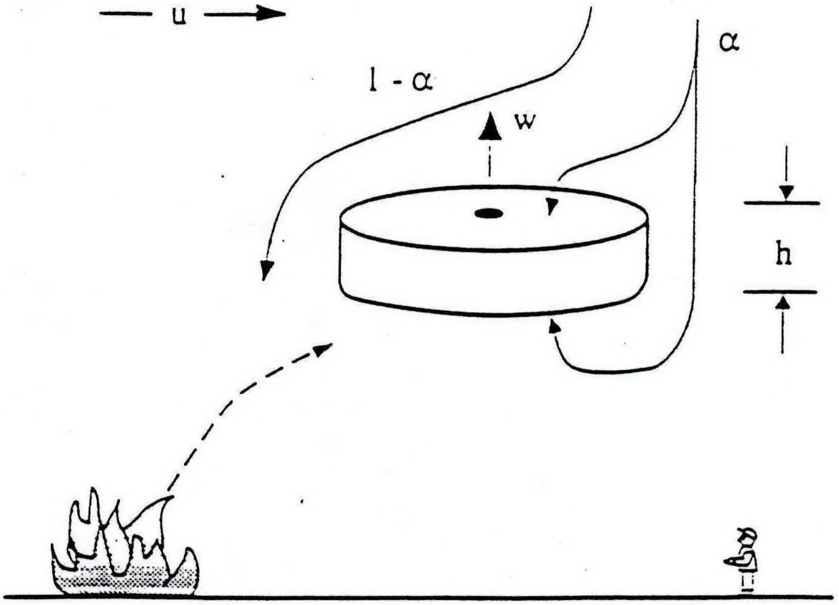

Figure 1. Volume element for smoke puff rising at velocity w while entraining α fraction of the ambient air.

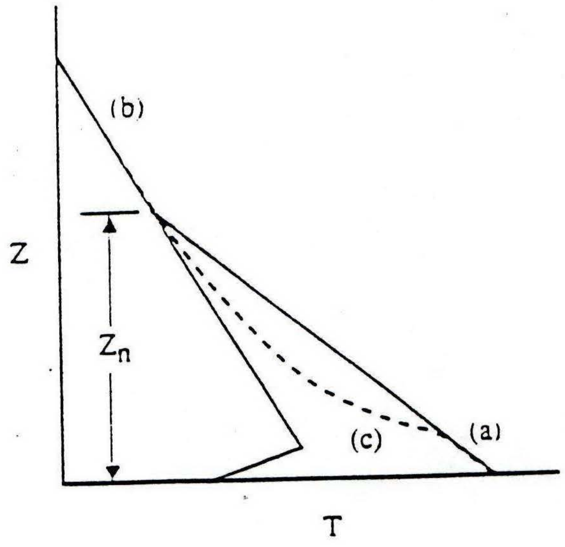

Figure 2. Schematic temperature profiles for
(a) the ambient air
(b) a dry adiabat
(c) a plume-rise trajectory.

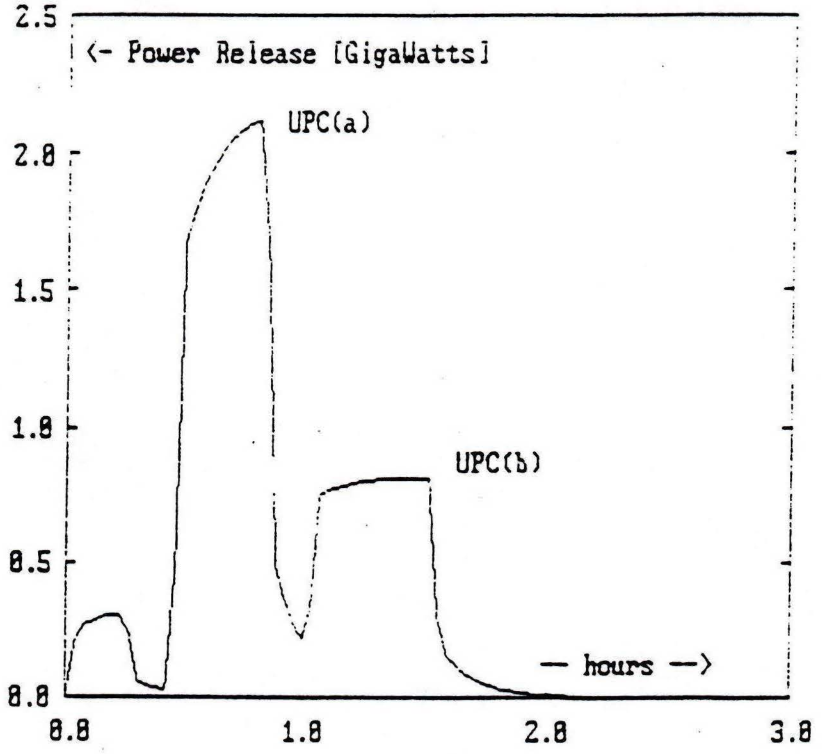

Figure 3. Computed power curve for one prescribed burn. Note that separate plume-height maxima were observed for (a) and (b).

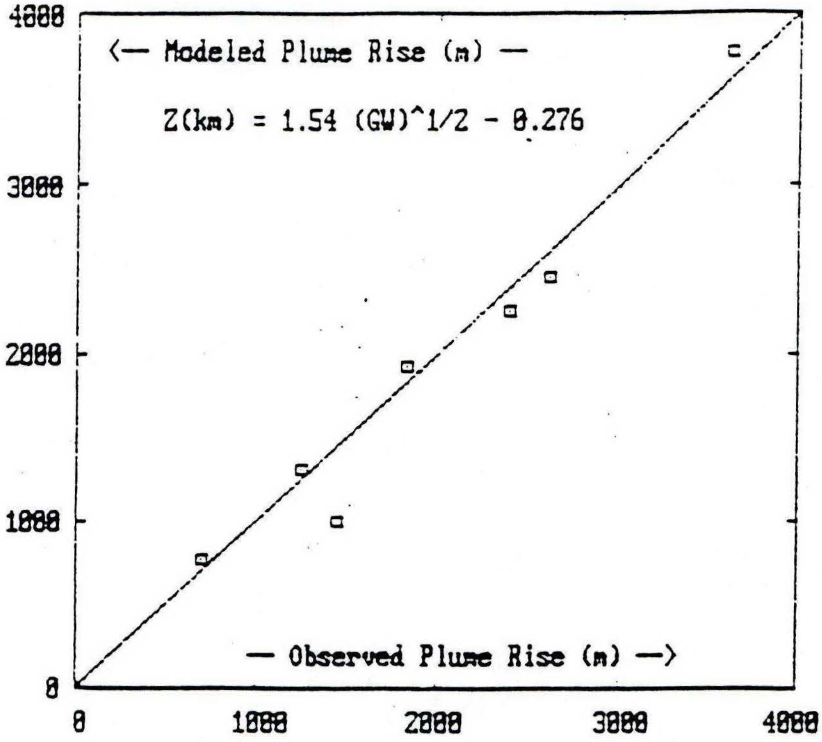

Figure 4. Comparison of modeled and observed plume-height maxima for the data of Table I.

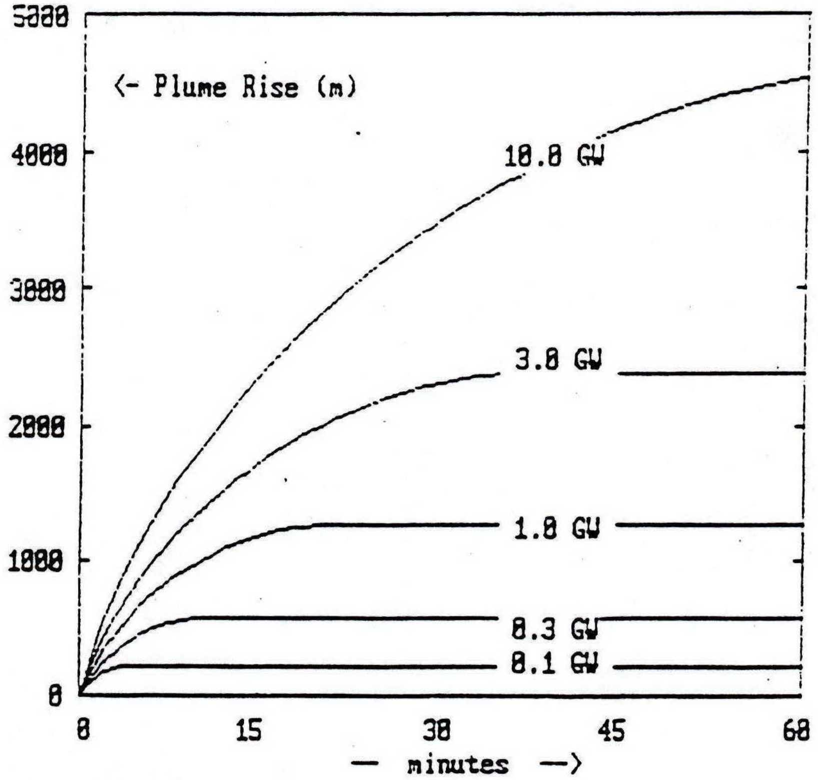

Figure 5. Computed plume rise dynamics by equations [11], [12c], [13] and [14].

APPENDIX C.

An Algorithm for Gaussian Puffs

H. Harrison
October 20, 1992

To estimate smoke concentrations:

- The EPM module returns time-dependent values for TSP emission rates [*R(t)* gm/s] and the fire's power [BTU/s] at three minute intervals, δT.

- In each δT PUFF creates one new puff for each fire. Each new puff carries with it a constant mass burden:

$$M = R(t) \cdot \delta T \qquad [1]$$

- As time progresses PUFF calculates the (x,y,z) positions of each puff's center. In this, the height above the ignition point, Z_I, is computed by the algorithm described in Appendix B. Note that the observations and parameters in this algorithm were evaluated from the plumes' *tops*. The puff-center heights above the local terrain, Z_L, are corrected by:

$$Z_L = Z_I + [H_o - H_{(x,y)}]/2 - \sigma \qquad [2]$$

[if $Z_L < 0$, then it is reset to zero.]

In [2] H_o is the terrain height above sea level at a puff's ignition point and $H_{(x,y)}$ is the terrain height above sea level at the puff's current horizontal position, (x,y). σ is a puff radius that will be described further in the next paragraph. Note that the divisor of 2 in this expression compromises between the extreme assumptions that

a: The puff heights above sea level are independent of the local terrain; that is, the puffs may bump into mountains without their vertical velocities being affected by slope of the terrain below, and

b: The puff heights, Z_L, above the *local* terrain, $H_{(x,y)}$, are the same as would be computed above the initial terrain H_o; that is, the puffs slide over the mountains as if they were flat.

- During each puff's evolution PUFF assigns a time-dependent radius, σ, as:

  $$\sigma^2 = \sigma^2_o + 2\ K\ t \qquad [3]$$

  At this moment, I am assuming:

  $$\sigma_o = 50 \text{ meters} \qquad [4a]$$

  and $$K = 50\ m^2s^{-1}. \qquad [4b]$$

- For a spherically symmetric Gaussian puff the tracer concentration at the surface is:

  $$C_s = [2/(2\pi)^{3/2}]\ [M/\sigma^3]\ \exp\left[\frac{-\ Z_L^2}{2\ \sigma^2}\right] \qquad [5]$$

  The factor of 2 immediately after the equal sign accounts for reflectivity at the surface.

Discussion

Equation [2] is the exact solution for a constant diffusivity. With turbulence from fires the "real" diffusivity is likely to decrease rapidly during the first 100 seconds or so, and then increase with something like a 5/3rds power of σ.

Equation [5] is for a spherically symmetrical Gaussian puff. The "real" puffs are more likely distorted by different values of $K_{x,y}$ and K_z. In our normal experience with plumes from stacks, K_y is on the order of 50 m^2s^{-1} and K_z is about 1 m^2s^{-1}. With intense vertical shear above fires, I would guess initial values of K_z exceeding 10^3 m^2s^{-1}, that might fall rapidly to about 10^2 m^2s^{-1} after 10^2 seconds or so, and then remain fairly constant for a few hundred seconds, before growing slowly again with the increasing spatial scales.

Together these guesses and arguments led me to

$$K_y \approx K_z \approx K \approx 50\ m^2s^{-1}$$

The guess of 50 meters for σ_o is approximately the width of actively flaming slash swaths.

Do you plunk for other numbers?

Discussion [con.]

The concentrations of all puffs add to one another over all surface area increments. To compute this double integral for every time step would consume a *lot* of time, more time (in my judgement) than is justified by the uncertainties of the model.

To simplify, therefore:

a. I assume that puffs only contribute to the grid cells immediately below them, and

b. I keep track only of the greatest concentrations contributed by any puff, in every grid cell, over the history of the current display.

How accurate is all this?

Bruce Turner claims CRSTER, a Gaussian plume model that he tested on 6 power stacks over a couple of years' data "gave results that were correct within a factor of two, more than half the time". It's hard to be sanquine that PUFF will do "as well" as this, and it might be much worse. For this reason I have chosen to display the peak surface concentrations on a logarithmic scale with factors of 3 separating adjacent contours. I strongly urge users not to ask more of PUFF, or any other model, than can reasonably be expected of it.